

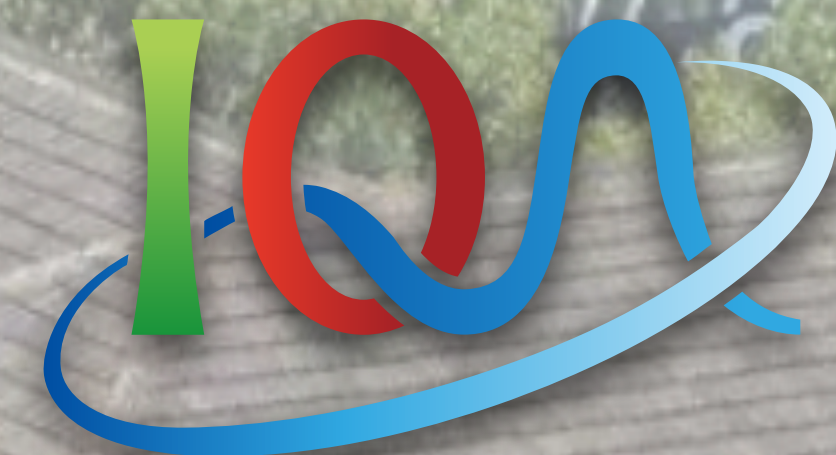
冷核介质效应：核部分子分布与中子皮

邢宏喜

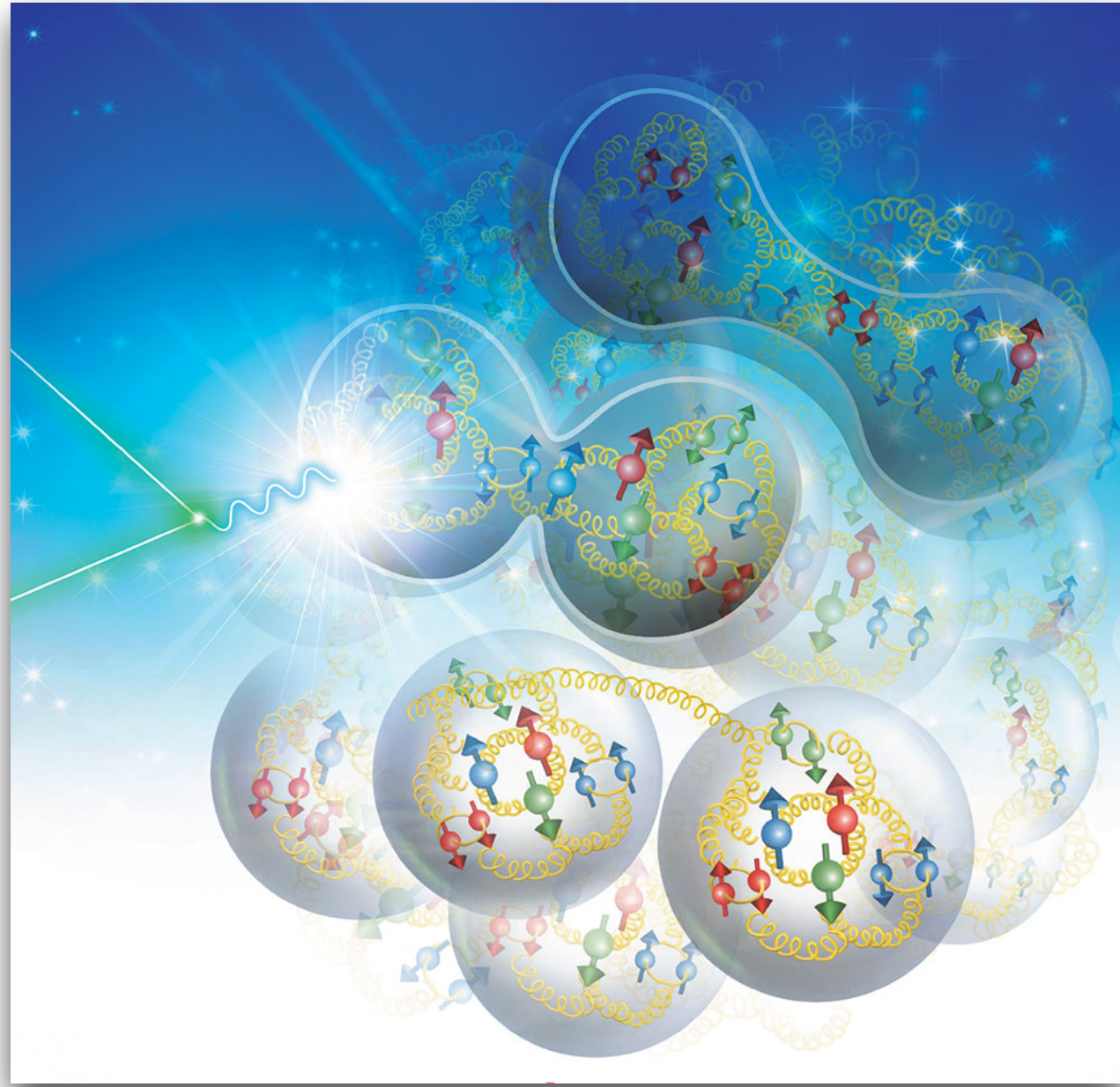
华南师范大学
量子物质研究院



高能与低能核物理交叉学术研讨会
上海, 2026.5.15-18

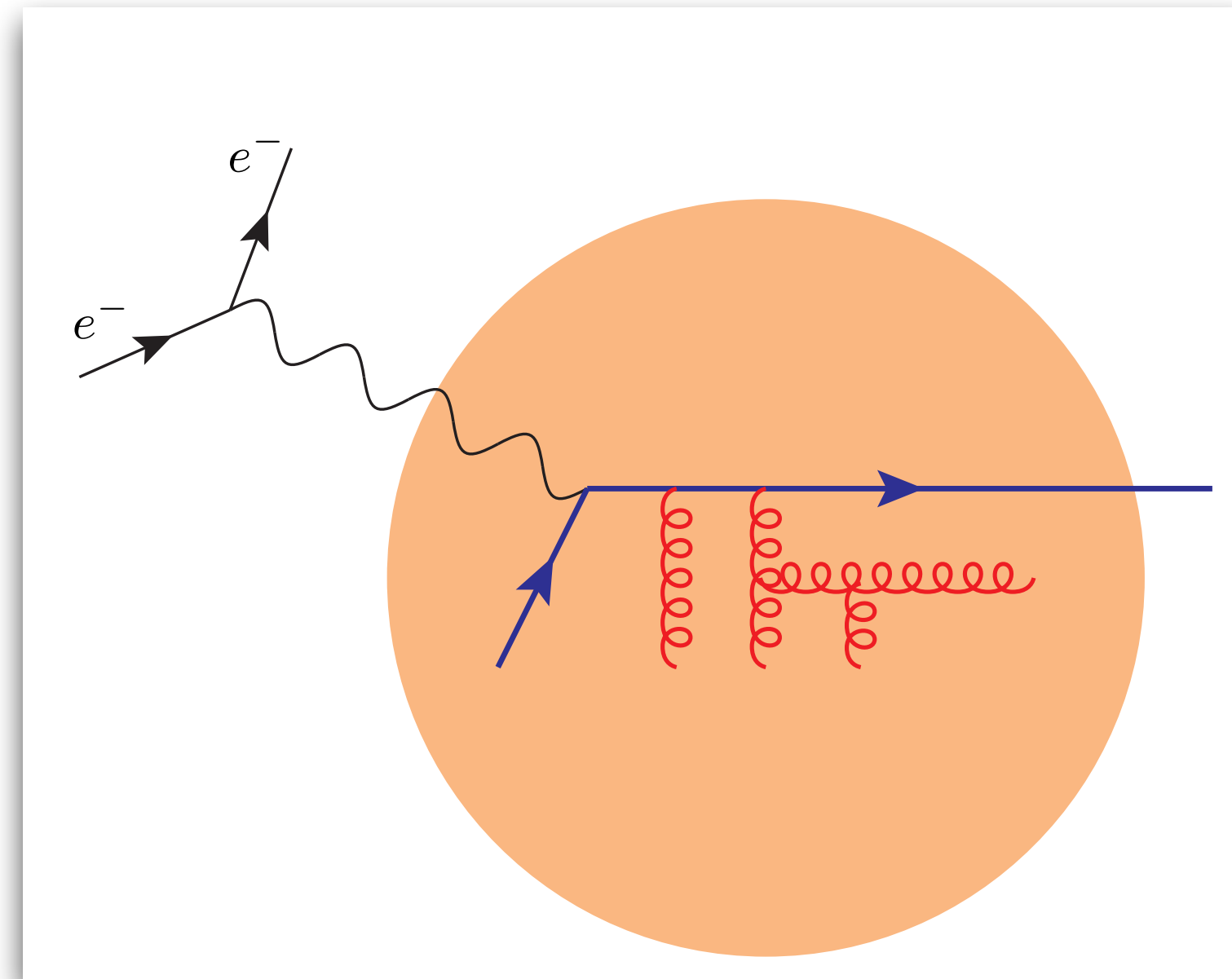


What are cold nuclear matter (CNM) effects?



Nuclear partonic structure

(Nuclear PDFs, SRC, Neutron skin...)



multiple scattering in nuclear medium

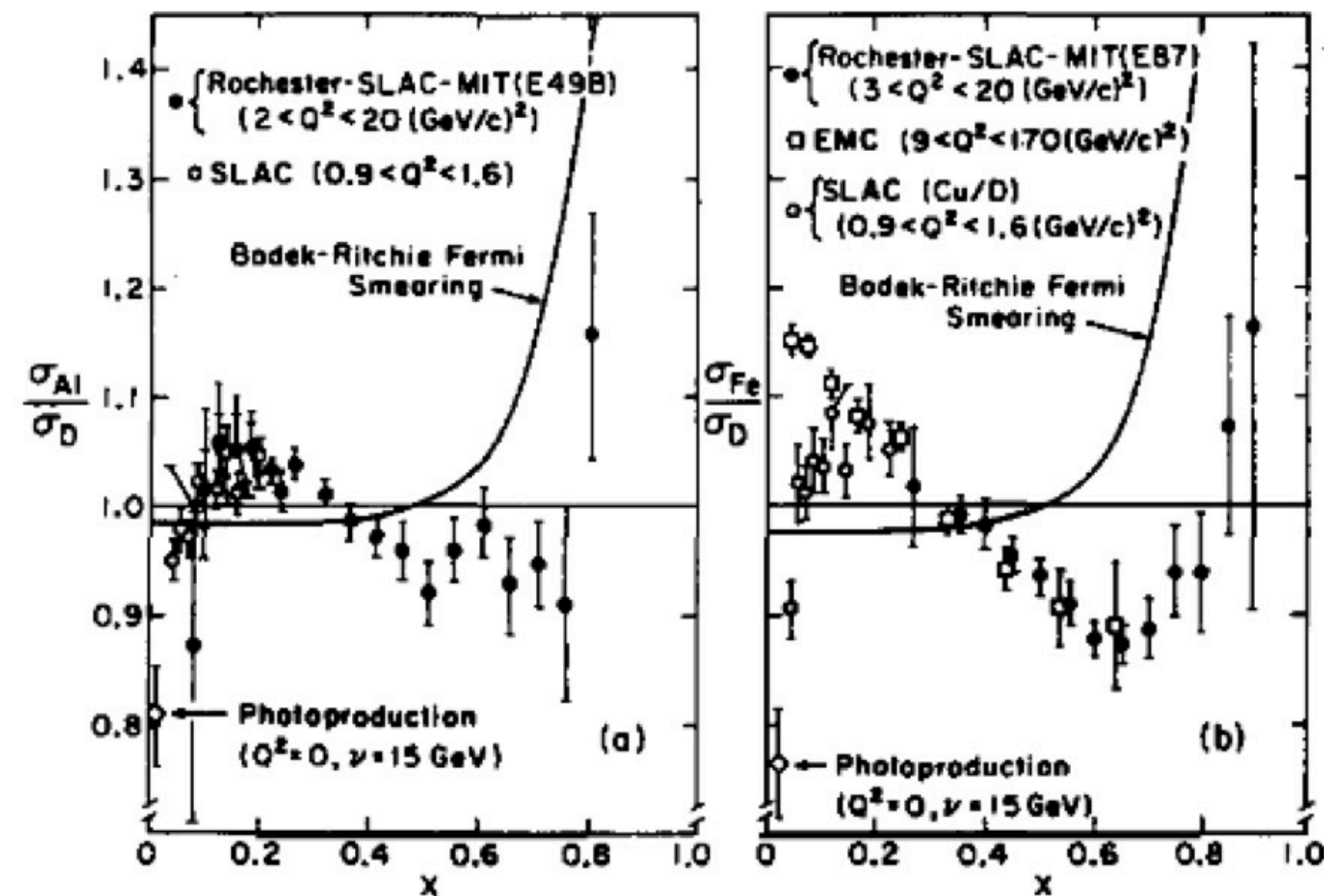
(Parton energy loss, Cronin effect ...)

- CNM effects can be accessed in pA and eA collisions where no hot medium forms
- CNM are a critical intersection point between low-energy and high energy nuclear physics

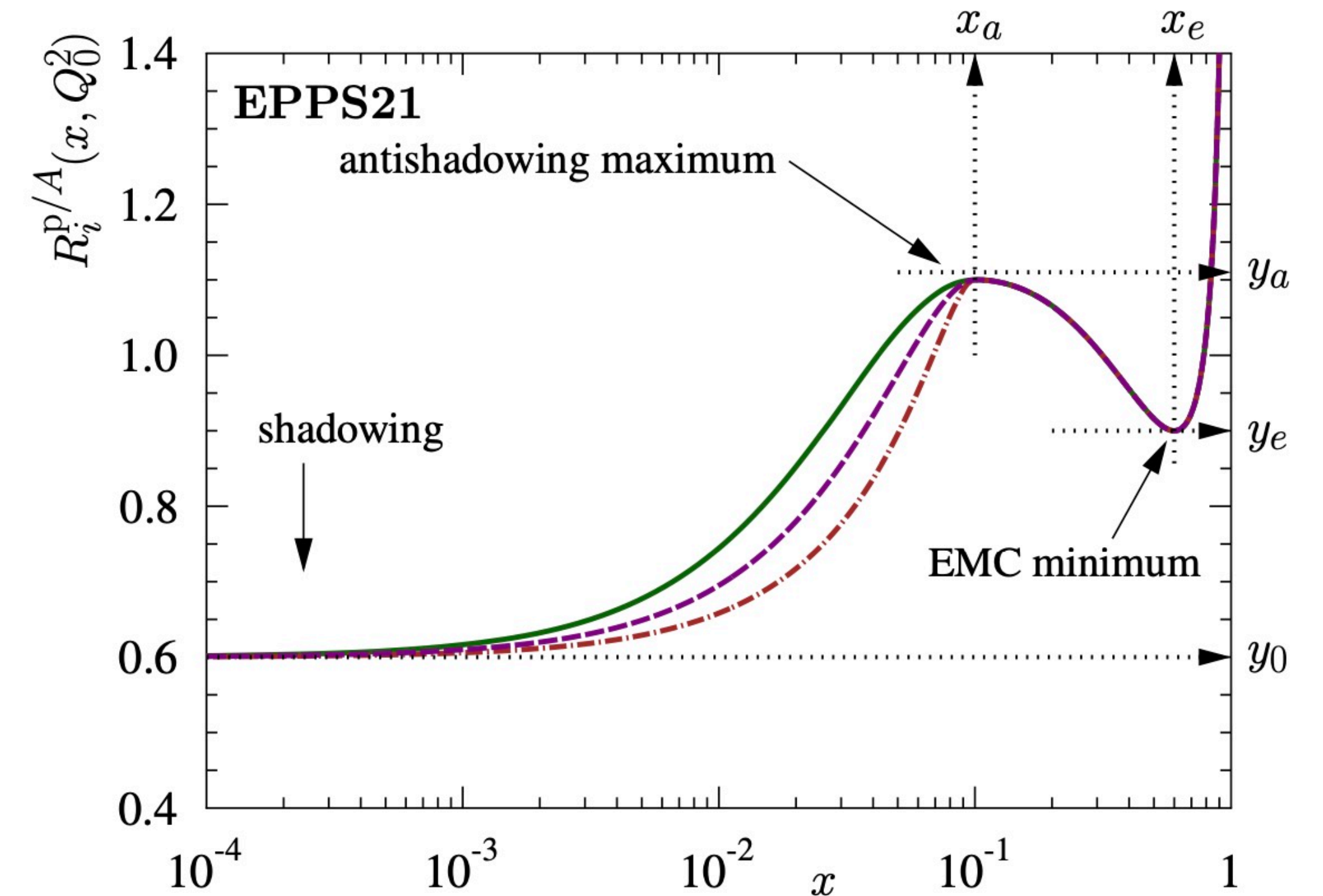
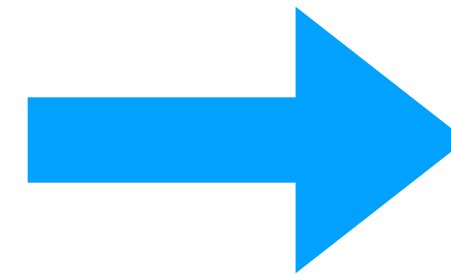
Long standing problems of nuclear partonic structure

♦ One-dimensional nuclear partonic structure

Four Decades of the EMC Effect



EMC Collaboration, 1983

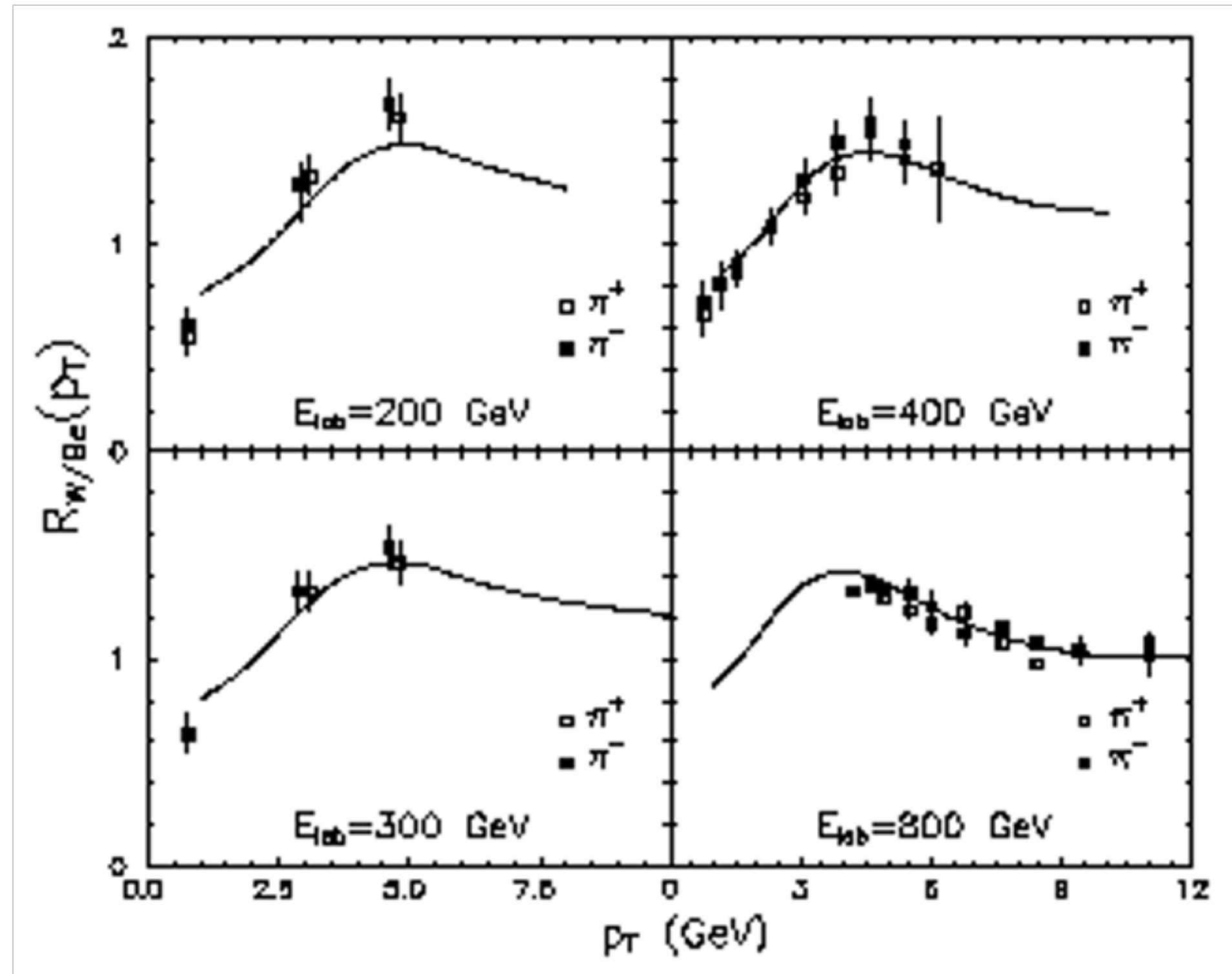


$$R_i^A = \frac{f_{i/A}(x, Q^2)}{f_{i/p}(x, Q^2)}$$

Long standing problems of nuclear partonic structure

◆ Three-dimensional nuclear partonic structure

Cronin effect

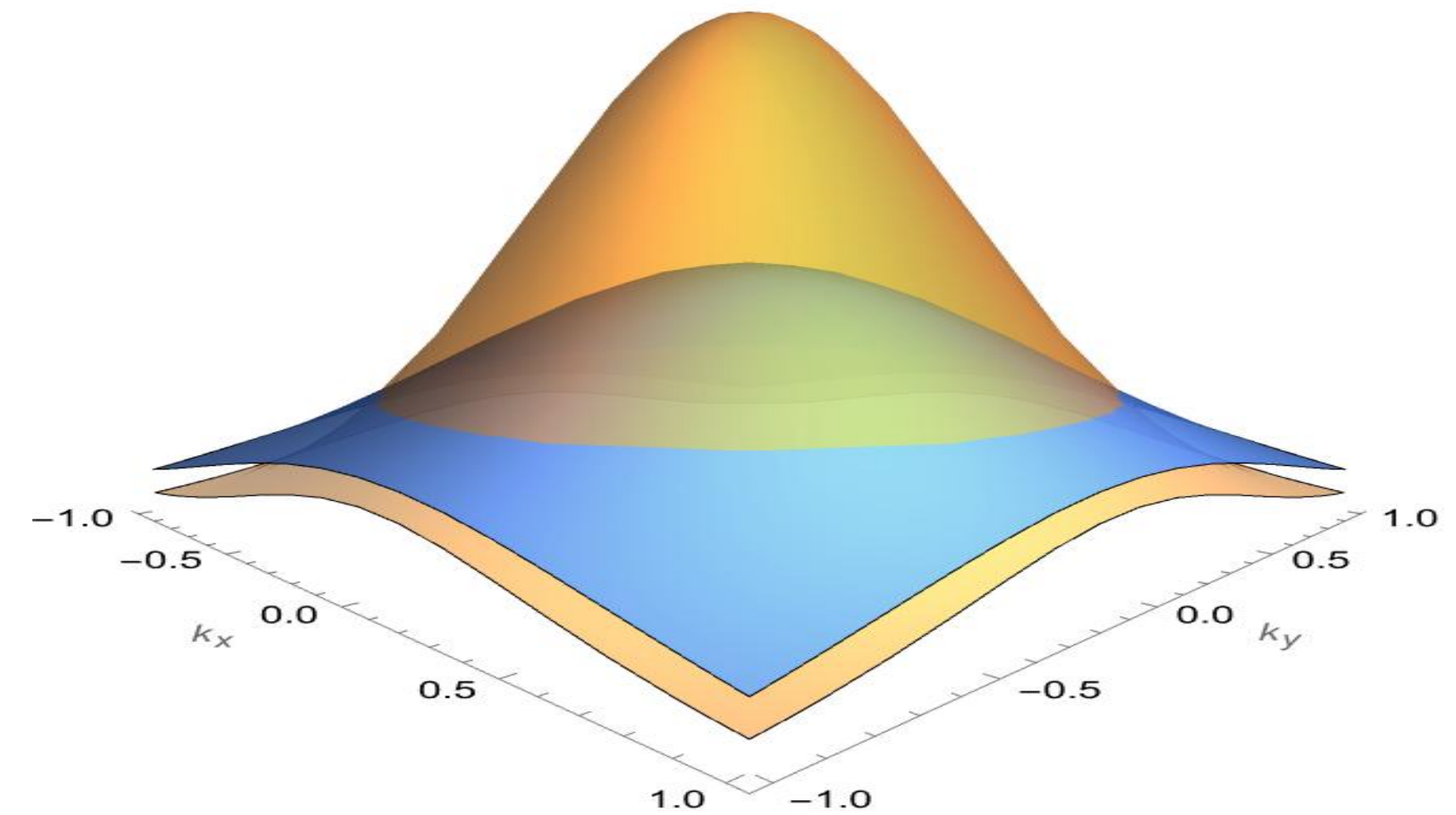


$$p + A \rightarrow \text{hadron}(p) + X$$

$$R(p_T) = \frac{B \, d\sigma_{pA}/d^2p_T}{A \, d\sigma_{pB}/d^2p_T}$$

E100 Collaboration, PRD 11, 3105 (1975)

- Naive Gaussian model

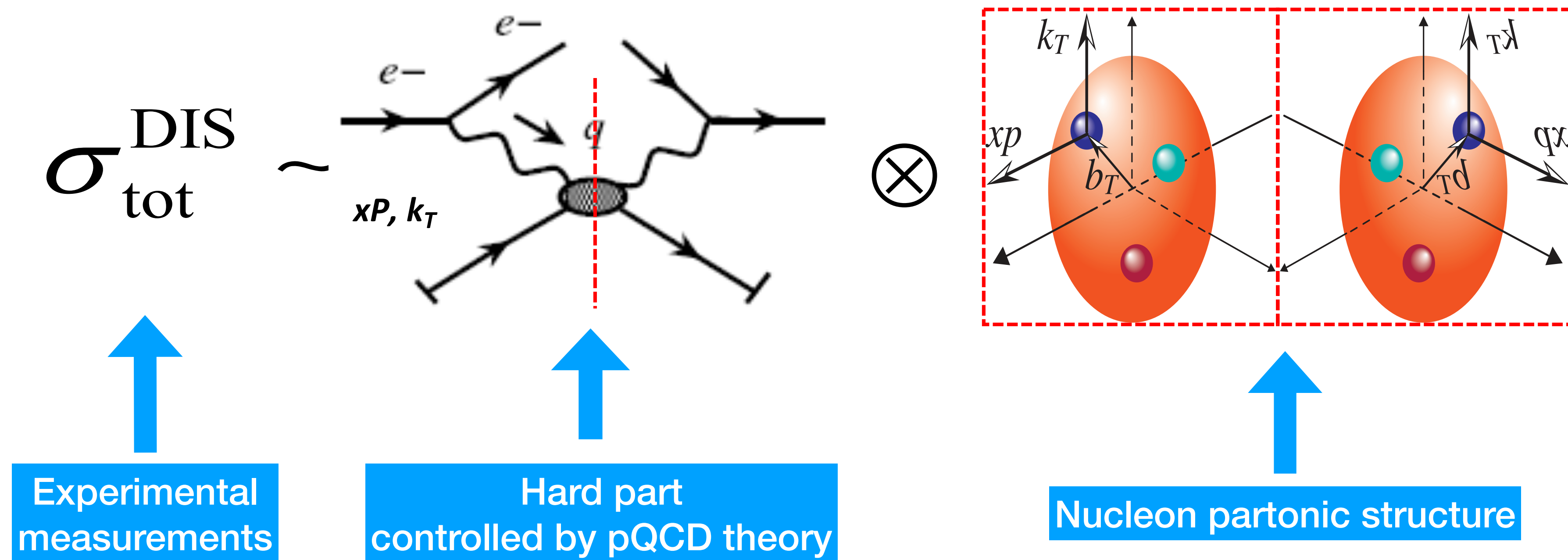


$$F_{i/p}(x, k_T) = f_{i/p}(x) \frac{e^{-k_T^2/\langle k_T^2 \rangle}}{\pi \langle k_T^2 \rangle}, \quad \langle k_T^2 \rangle_A \rightarrow \langle k_T^2 \rangle_p + \left\langle \frac{2\mu^2 L}{\lambda} \right\rangle \xi^2$$

How to probe the nucleon/nuclear partonic structure?

- ◆ Indispensable joint efforts from experiments and **QCD theory**

QCD factorization theorem



Methodology for global extraction of PDFs

Fitting Framework

Construction of χ_{global}^2 from χ_n^2

χ_n^2 Construction

Generation of Theory Data

PDFs Evolution

Coefficient functions

Experimental Data

PDF Parametrization

Minimization of χ_{global}^2

Hessian Matrix

Constructed sampling the χ_{global}^2 function

Best fit

Uncertainties

PDF eigen vectors set
using Hessian Method

MC Sampling of parameter space: new parameters introduced

理论

+

计算

+

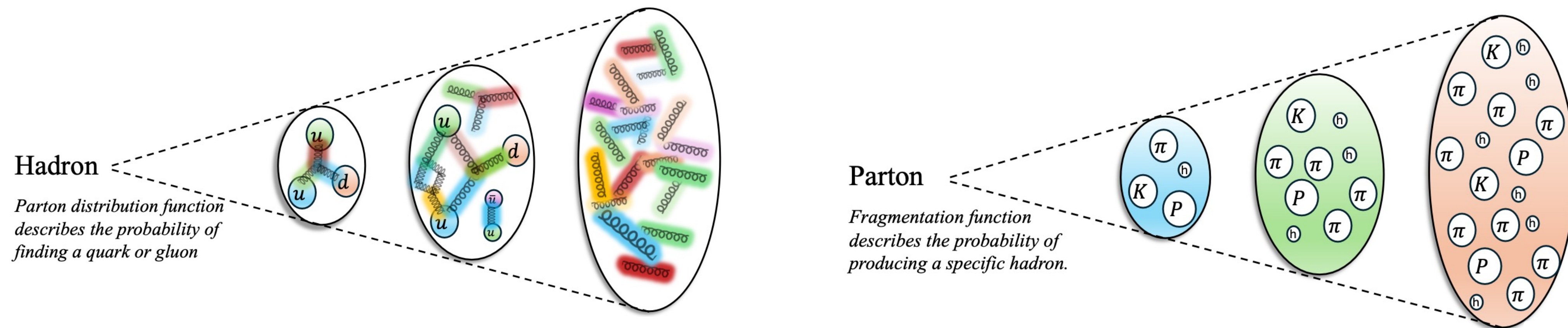
实验



Recent efforts from NPC collaboration

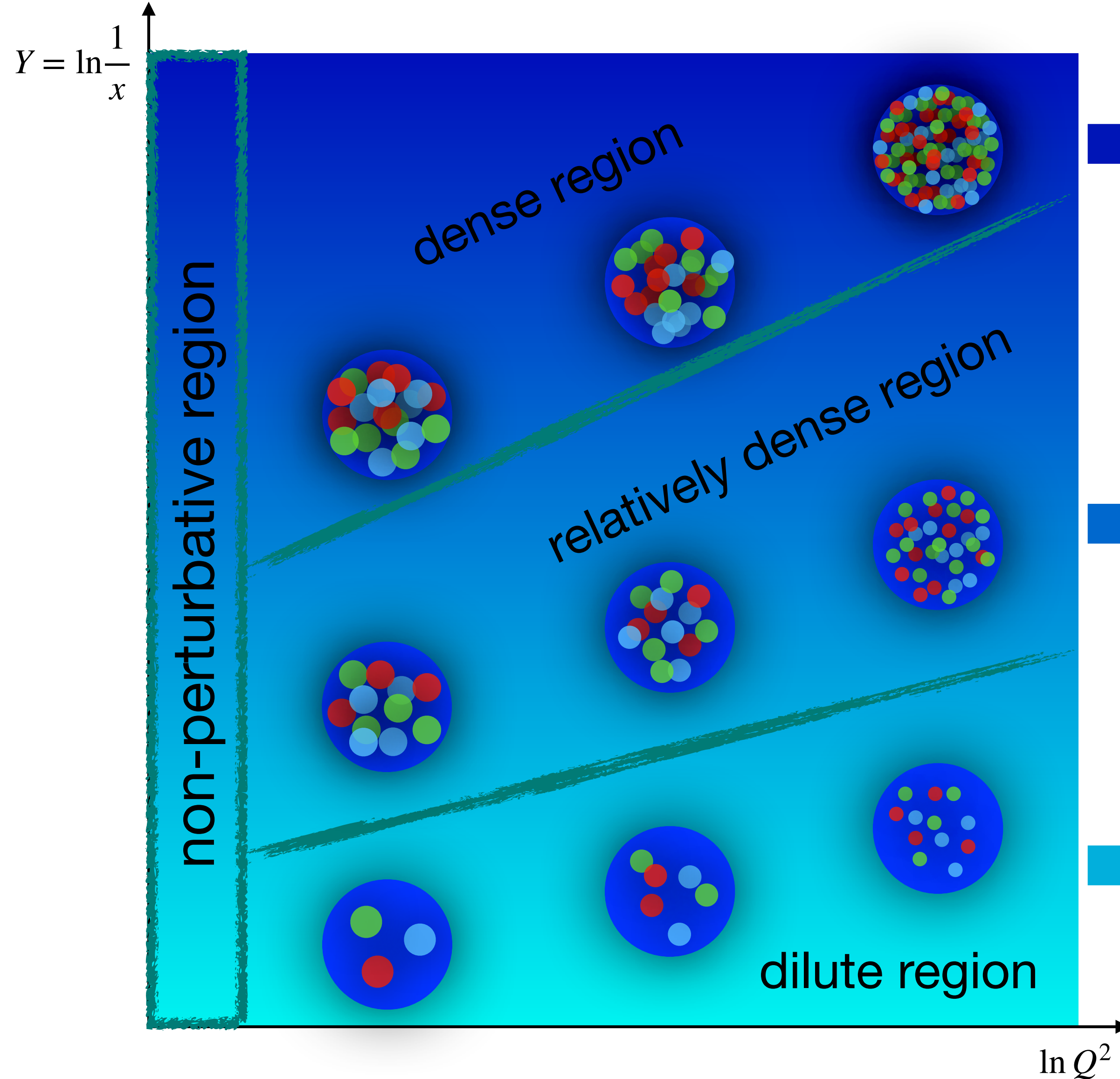
◆ Nonperturbative Physics Collaboration, start from 2023

SJTU (高俊) + IMP (沈晓民、赵宇翔) + SCNU (邢宏喜)



- ◆ Parton fragmentation in vacuum at NLO and NNLO (2 PRL + 2 PRD)
- ◆ Parton fragmentation in e^+e^- at N3LO (1 PRL)
- ◆ Parton fragmentation in CNM (appear soon)
- ◆ Proton spin structure (on going)

QCD “phase diagram” for nuclei



Dense region: $x \ll \mathcal{O}(1)$

Probing length $\lambda \sim 1/xp \gg L \sim A^{1/3}$

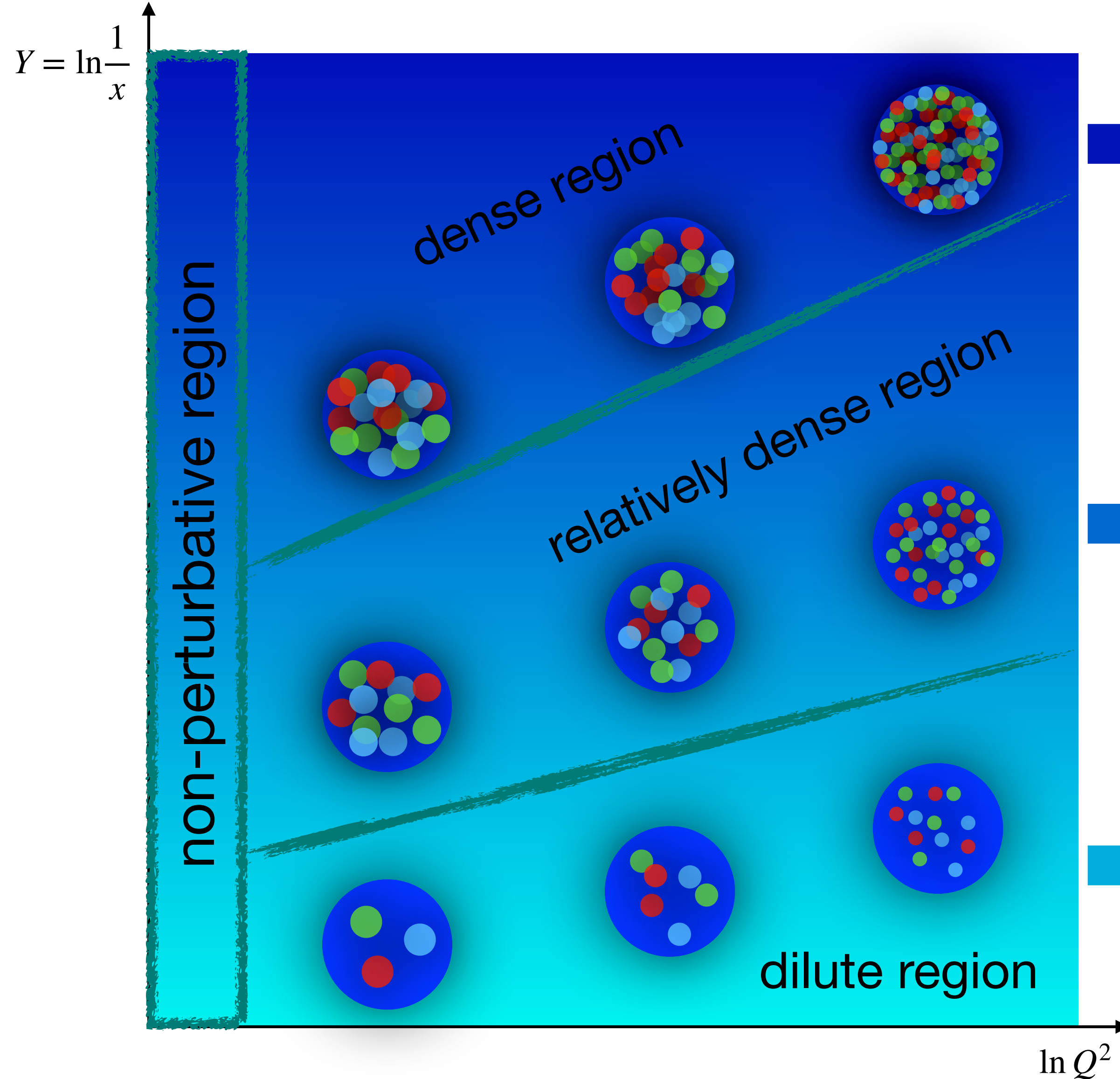
Relatively dense region: $x \lesssim \mathcal{O}(1)$

Probing length $\lambda \sim 1/xp \lesssim L \sim A^{1/3}$

Dilute region: $x \sim \mathcal{O}(1)$

Probing length $\lambda \sim 1/xp \ll L \sim A^{1/3}$

QCD factorization from dilute to dense region



Color Glass Condensate (CGC)

Wilson lines, nonlinear BK/JIMWLK evolution

See review: Gelis, Iancu, Venugopalan, 2003

High-twist formalism

Multi-parton correlation, DGLAP-type evolution

Qiu, Stermann, 1991

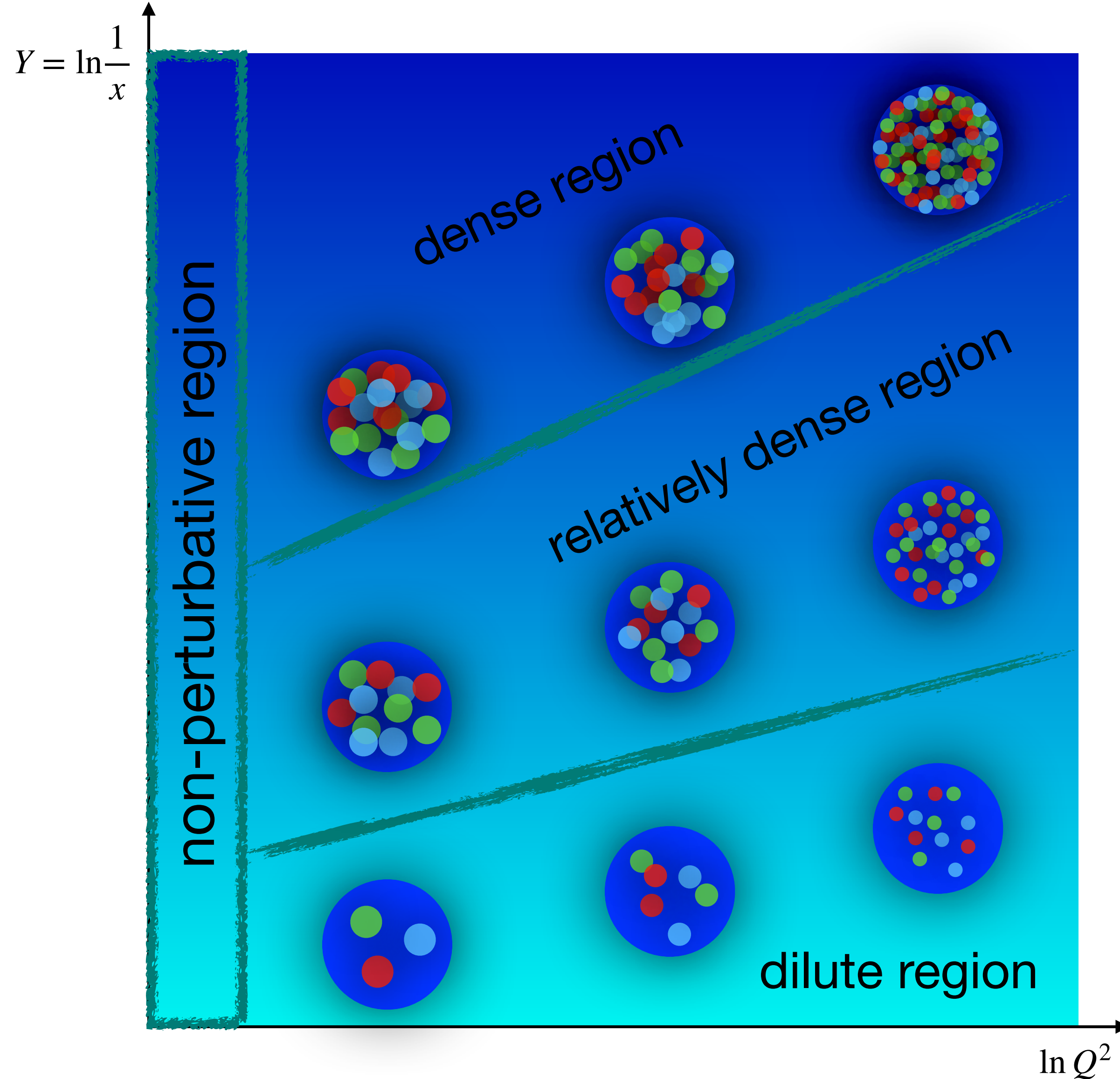
Kang, Wang, Wang, **Xing**, 2014

Leading twist collinear factorization

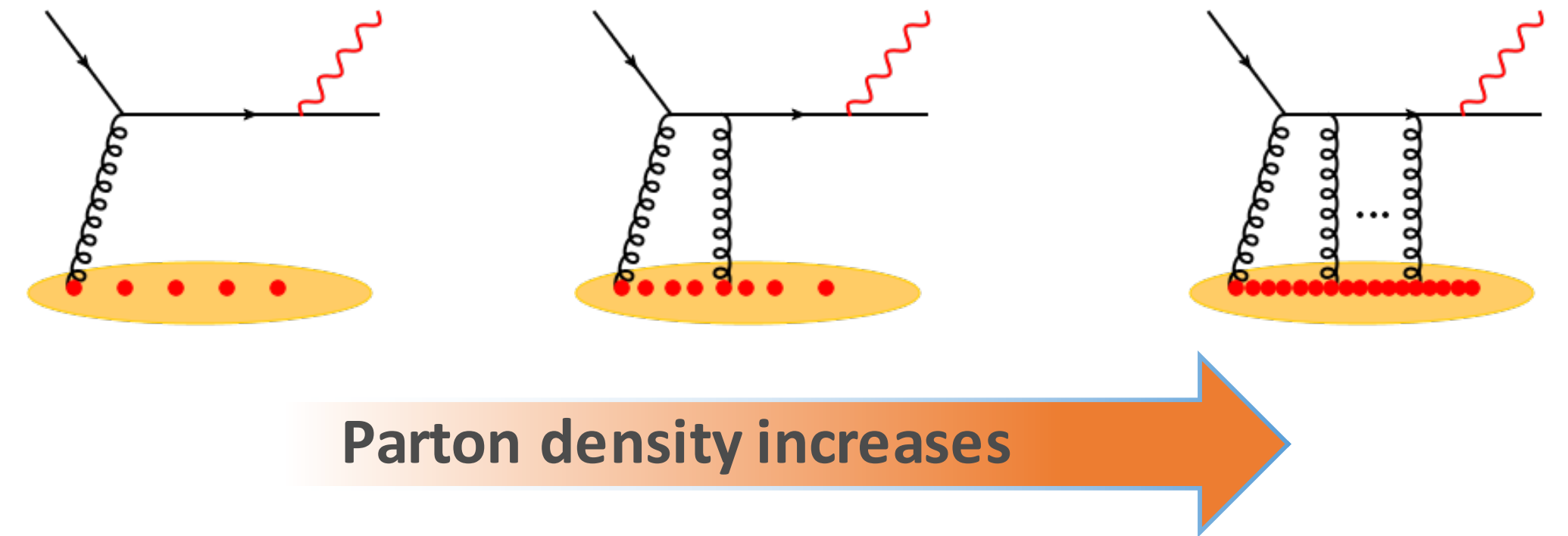
PDF, DGLAP evolution

Collins, Soper, 1981

A unified factorization from dilute to dense region



◆ Photon production in pA collisions



$$E_\gamma \frac{d\sigma^{\text{CGC}_{\text{sub}}}}{d^3\mathbf{p}_\gamma} \Big|_{p_{\gamma\perp} > Q_s} = E_\gamma \frac{d\sigma^{\text{LT}}}{d^3\mathbf{p}_\gamma} + E_\gamma \frac{d\sigma^{\text{T4}}}{d^3\mathbf{p}_\gamma} + \dots$$

leading twist

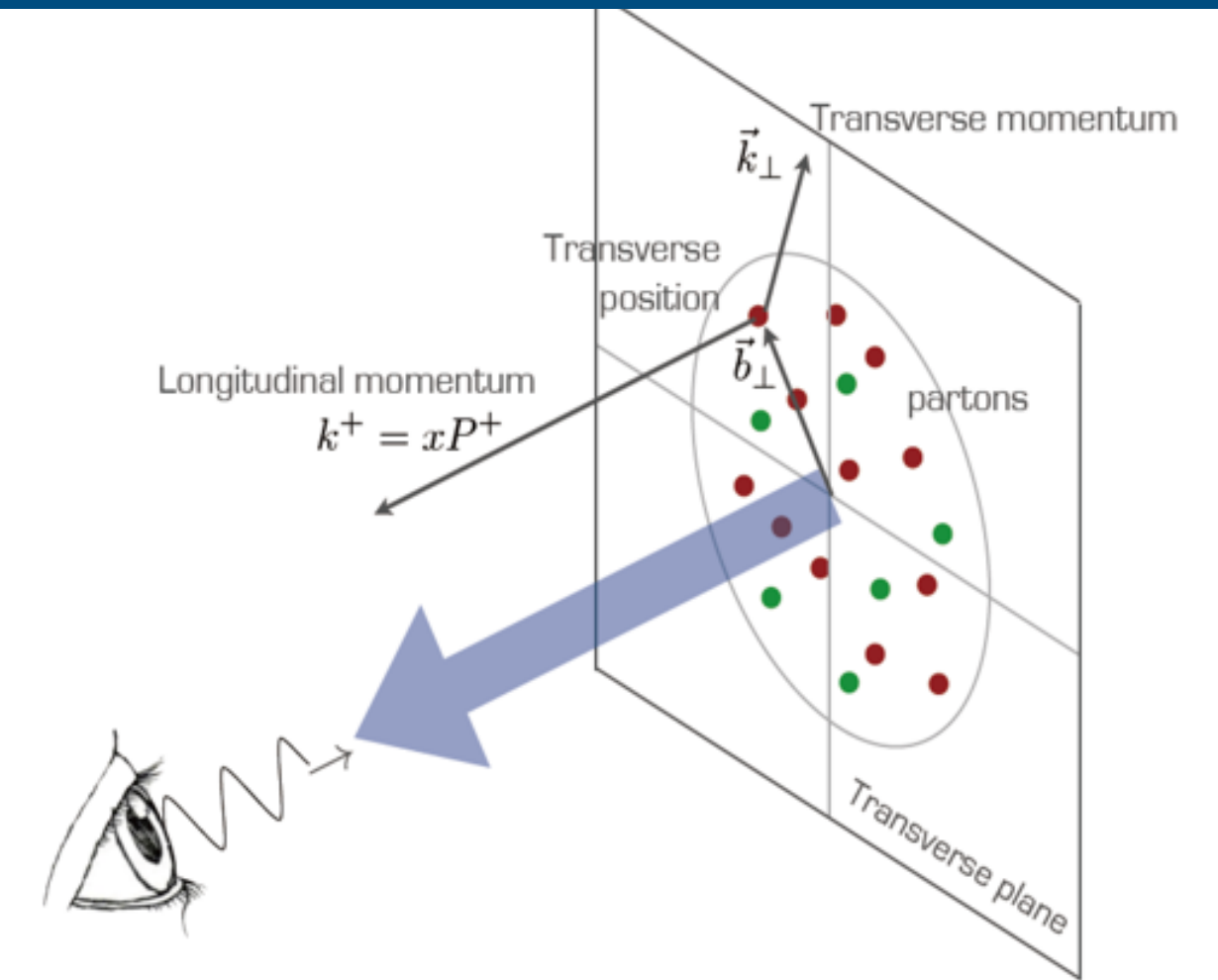
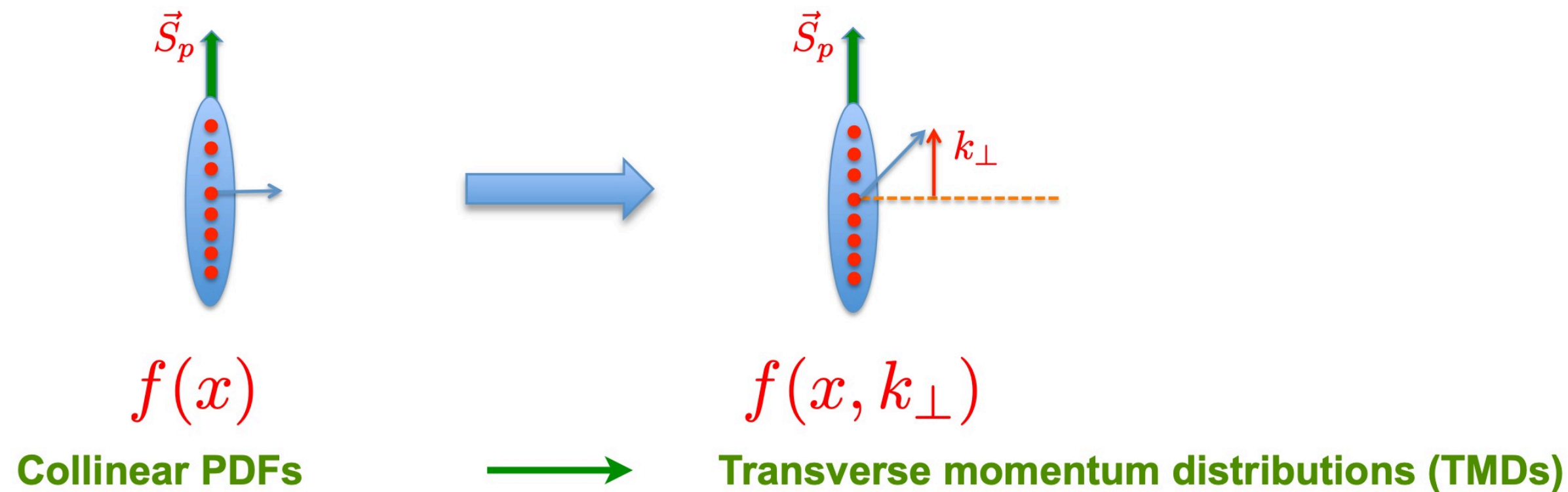
twist-4

Fu, Kang, Salazar, Wang, **HX**, PRL 2025

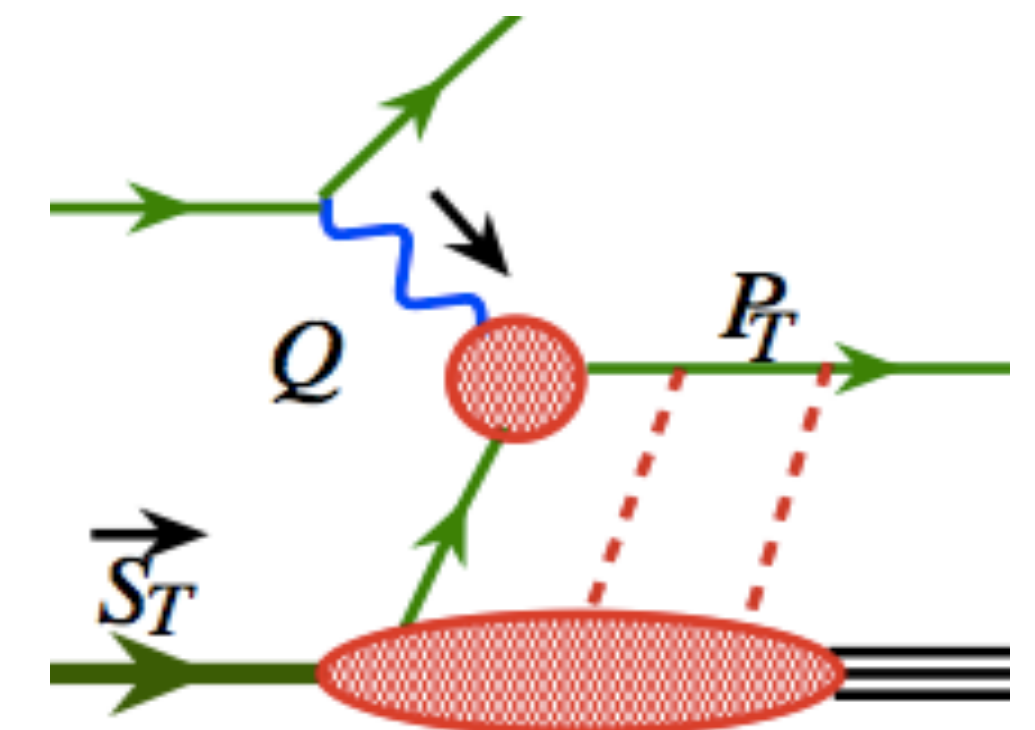
Fu, Kang, Salazar, Wang, **HX**, PRD 2025

Global analysis of nuclear TMD

◆ Transverse momentum dependent PDFs (TMDs)



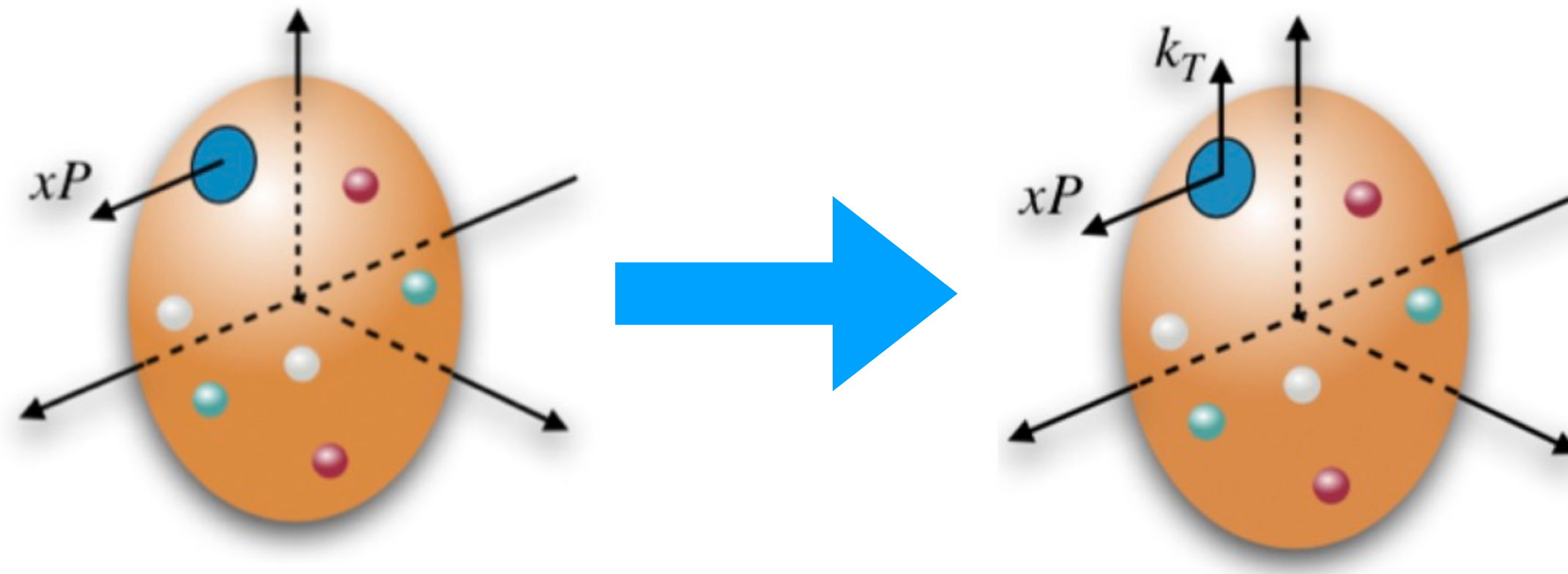
- Probing nucleon 3D structure requires two momentum scales
- Hard scale $Q_1 \gg 1/fm$ localizes the probes (particle nature of quarks/gluons)
- Soft scale $Q_2 \sim 1/fm$ accesses the transverse motion of quarks/gluons



SIDIS: $Q \gg P_T$

Global analysis of nuclear TMD

◆ From collinear (1D) to TMD (3D)



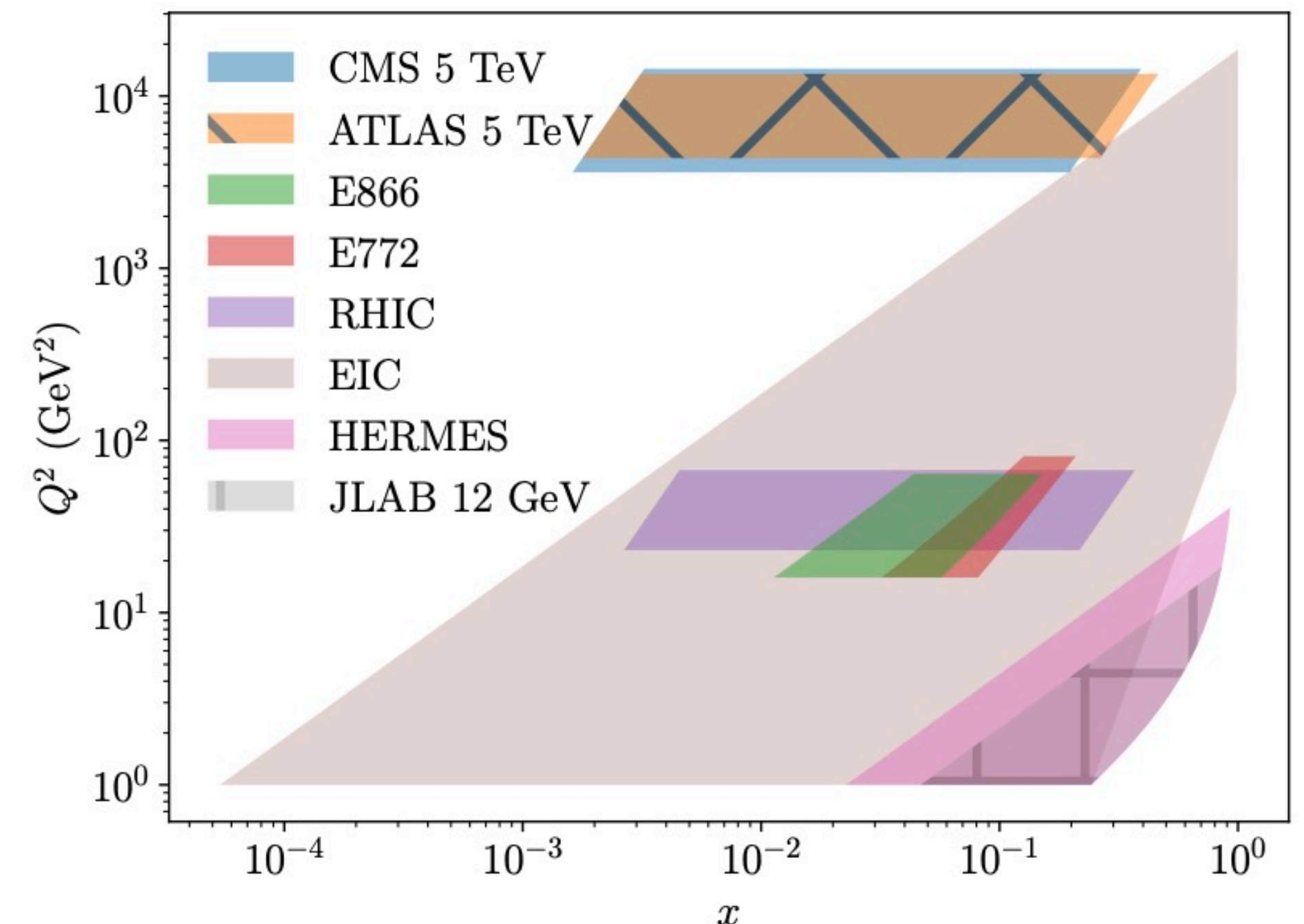
Collaboration	Process	Baseline	Nuclei	N_{dat}	χ^2
HERMES [36]	SIDIS (π)	D	Ne, Kr, Xe	27	16.3
RHIC [44]	DY	p	Au	4	2.0
E772 [42]	DY	D	C, Fe, W	16	20.1
E866 [43]	DY	Be	Fe, W	28	43.3
CMS [45]	γ^*/Z	NA	Pb	8	9.7
ATLAS [46]	γ^*/Z	NA	Pb	7	13.1
Total				90	105.2

Drell-Yan Measurements

- $R_{AB} = \frac{d\sigma_A}{dq_\perp} / \frac{d\sigma_B}{dq_\perp}$
- E866
- E772
- Prelim. RHIC
- $d\sigma/dq_\perp$ (p Pb)
- ATLAS
- CMS

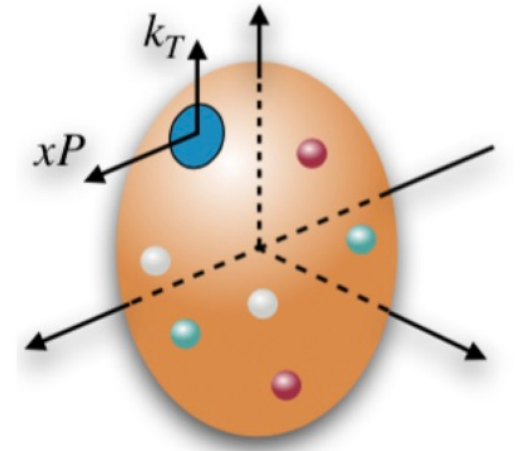
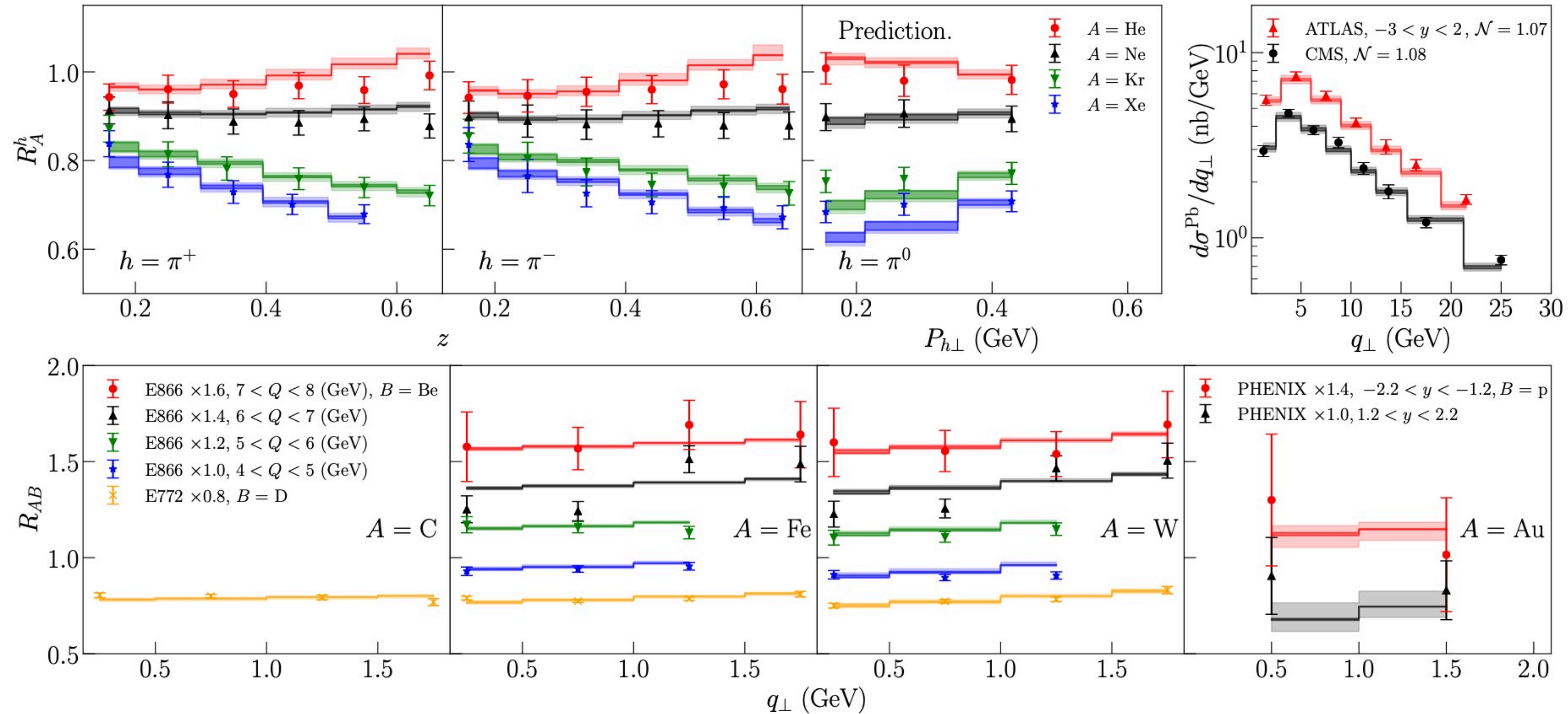
SIDIS Measurements

- Multiplicity ratio $R_h^A = M_h^A / M_h^D$.
- HERMES 2007
- Prelim. JLab
- Planned JLab
- Possible EIC.



Global analysis of nuclear TMD

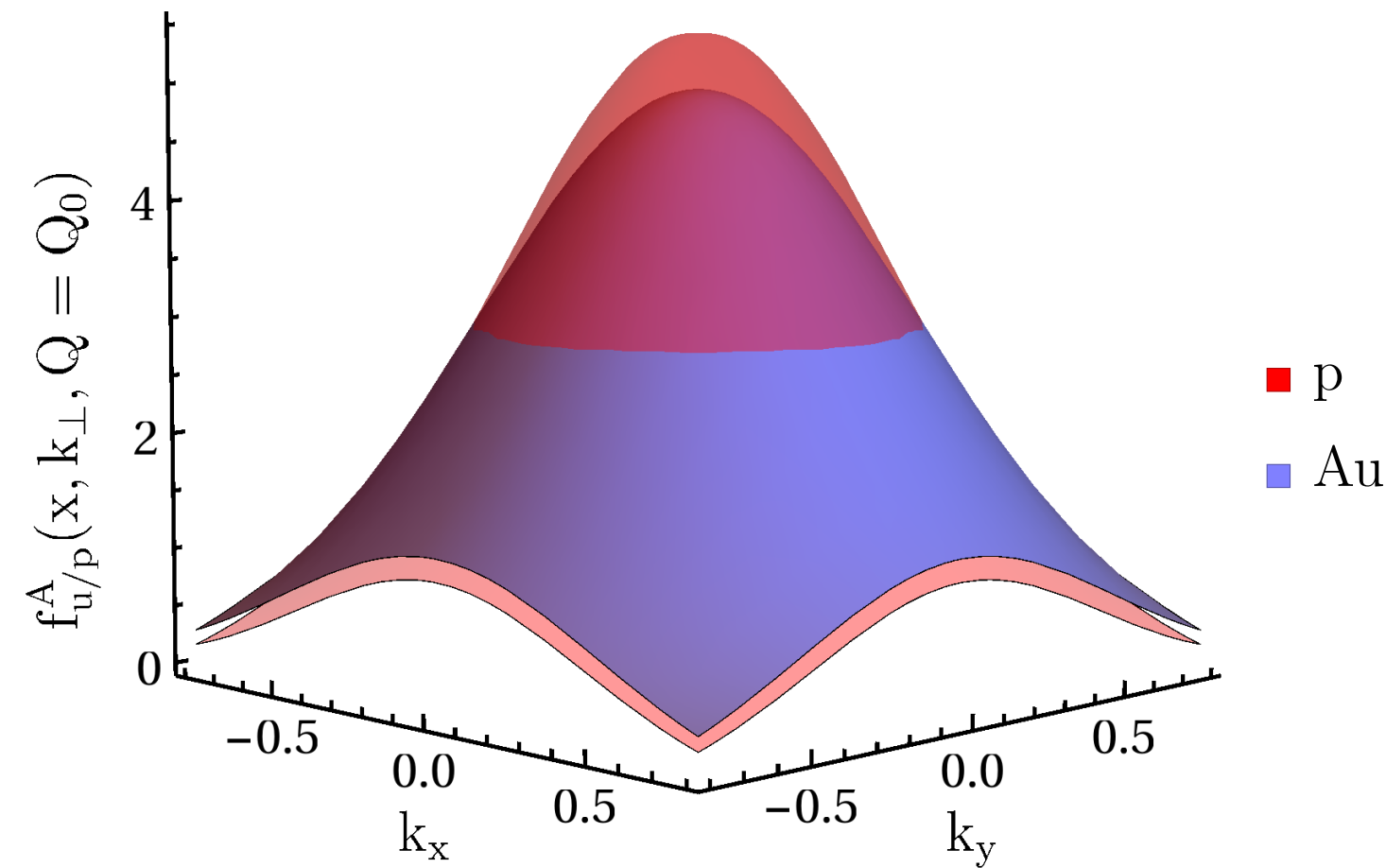
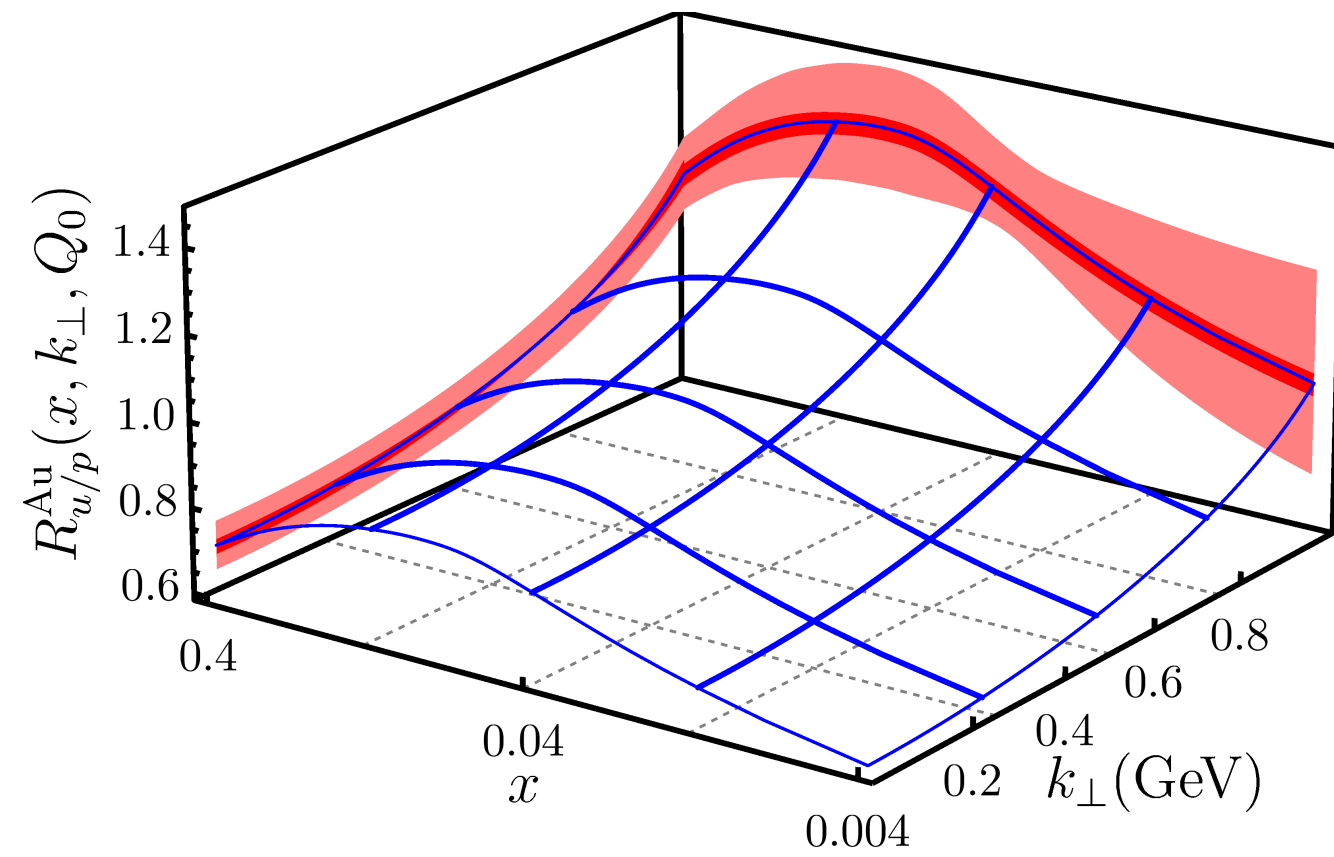
Alrashed, Anderle, Kang, Terry, **HX**, PRL 2022



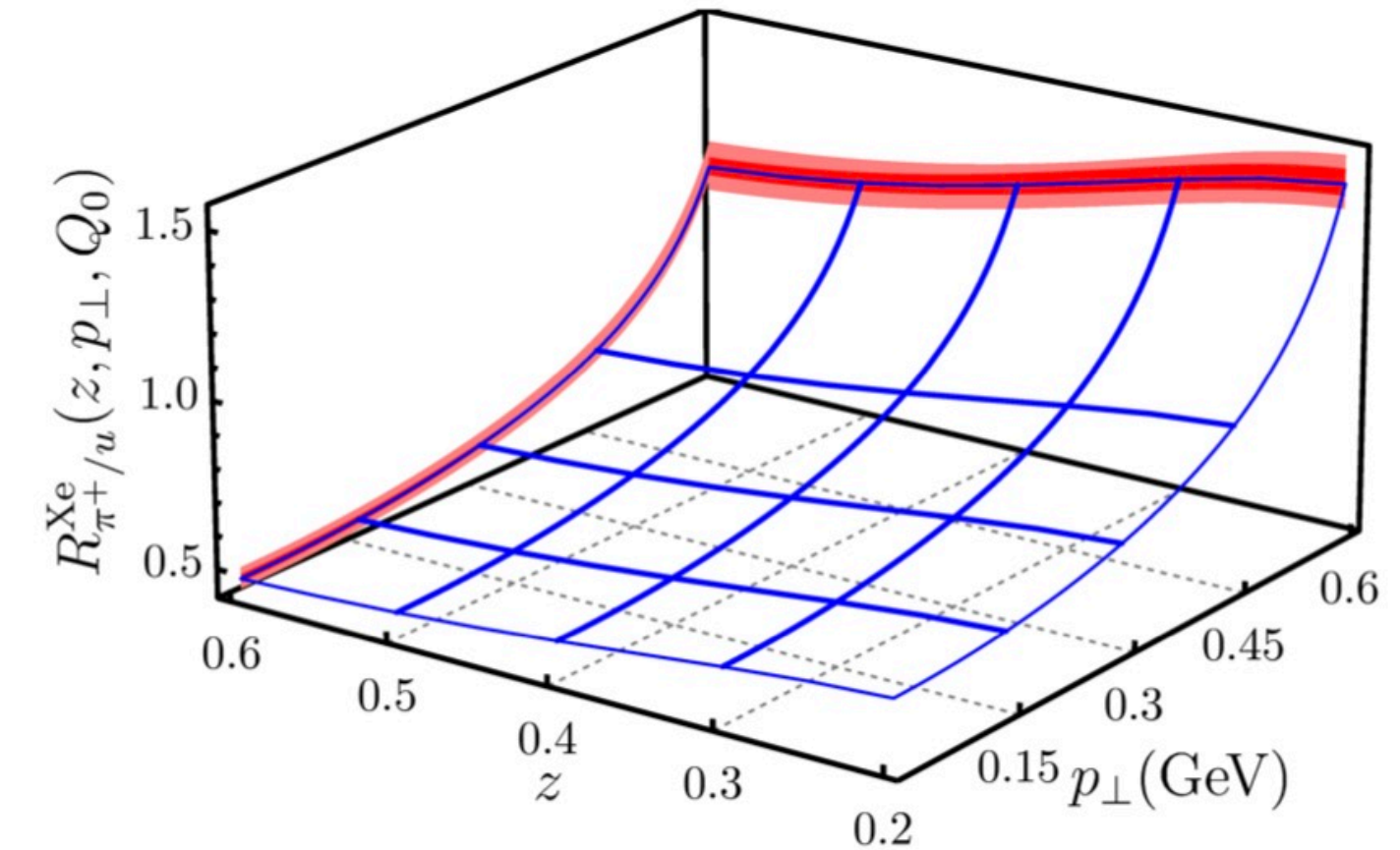
Reasonable good overall description on world data from HERMES, FNAL, RHIC, LHC

Three-dimension imaging in nuclei

$$R_{u/p}^{\text{Au}}(x, k_{\perp}, Q_0) = \frac{f_{u/p}^{\text{Au}}(x, k_{\perp}, Q_0)}{f_{u/p}(x, k_{\perp}, Q_0)}$$



$$\mathcal{R}_{\pi^+/u}^{\text{Xe}}(z, p_{\perp}, Q_0) = \frac{D_{\pi^+/u}^{\text{Xe}}(z, p_{\perp}, Q_0)}{D_{\pi^+/u}(z, p_{\perp}, Q_0)}$$



- **First time quantitative determination of nuclear TMDs**
- **Identification of transverse momentum broadening in nuclei**

Alrashed, Anderle, Kang, Terry, **HX**, PRL 2022

Alrashed, Kang, Terry, **HX**, Zhang, 2312.09226

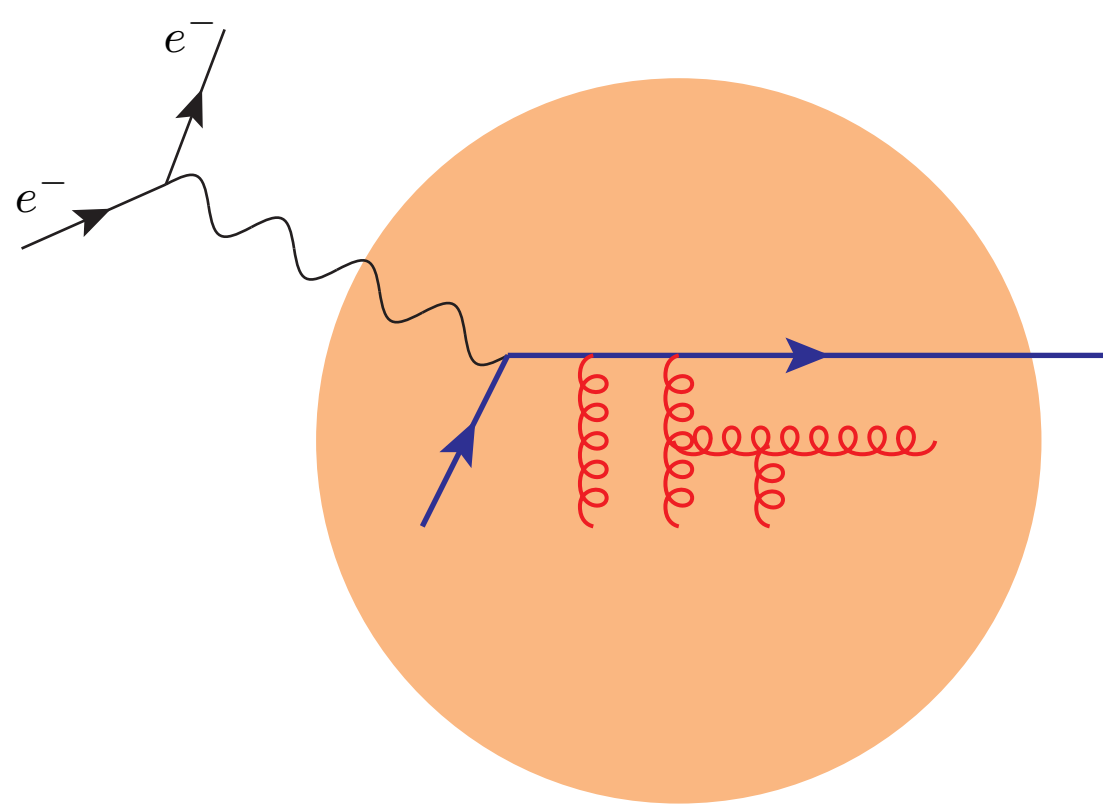
Zhou, Kang, **HX**, 2606.xxxxx

Global analysis of jet transport parameter in CNM

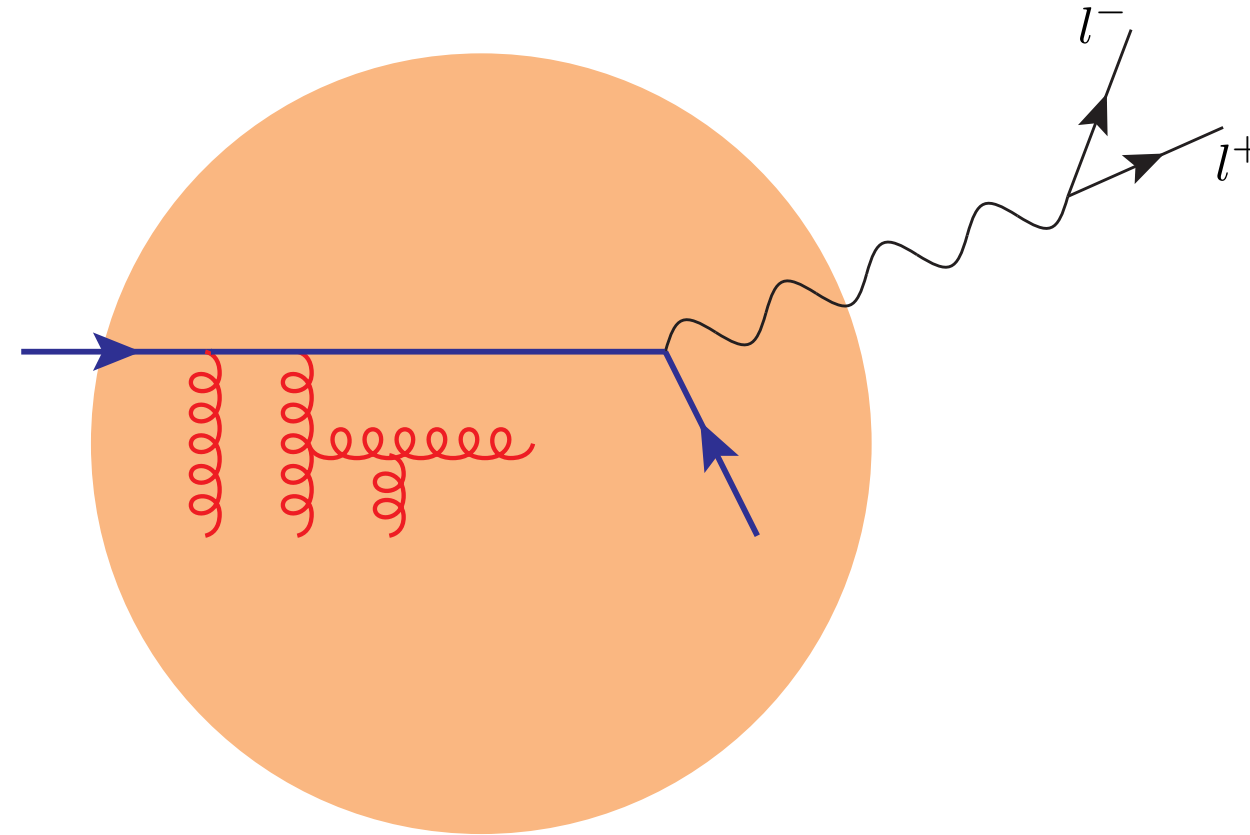
◆ Transverse momentum broadening in nucleus

$$\Delta\langle\ell_{hT}^2\rangle = \langle\ell_{hT}^2\rangle_{eA} - \langle\ell_{hT}^2\rangle_{ep} = \left(\frac{4\pi^2\alpha_s}{N_c}z_h^2\right) \frac{\sum_q e_q^2 T_{qg}(x_B, 0, 0) D_{h/q}(z_h)}{\sum_q e_q^2 f_{q/A}(x_B) D_{h/q}(z_h)}$$

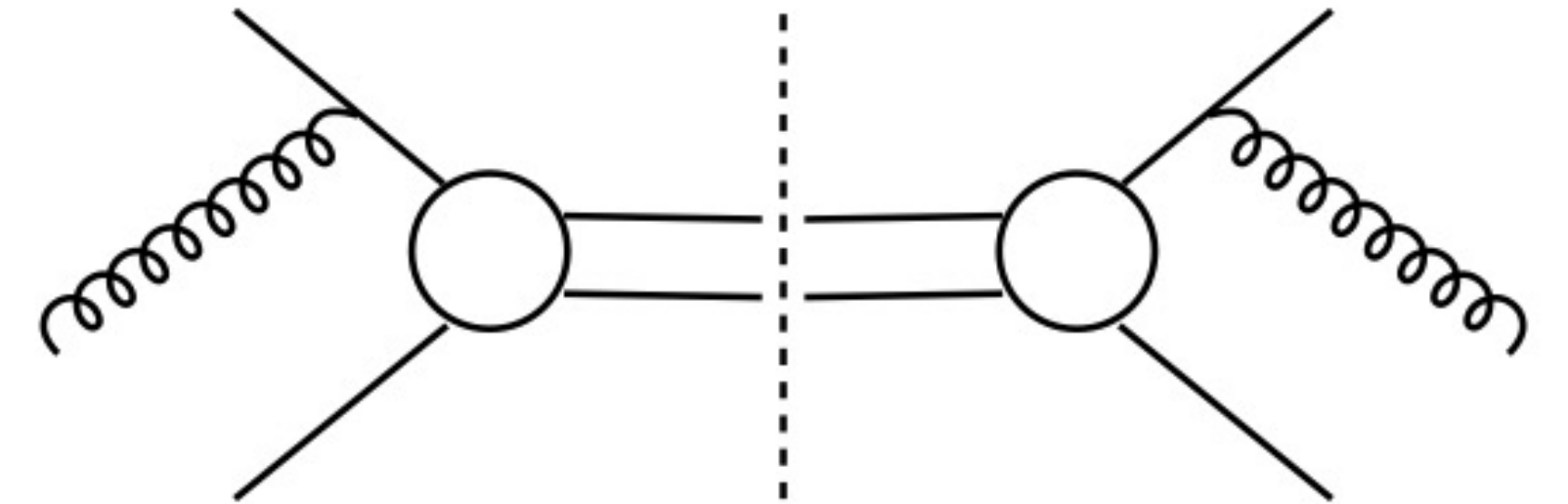
Jet transport parameter: $T_{qg}(x_B, 0, 0, \mu^2) \approx \frac{N_c}{4\pi^2\alpha_s} f_{q/A}(x_B, \mu^2) \int dy^- \hat{q}(\mu^2, y^-)$



SIDIS off nucleus



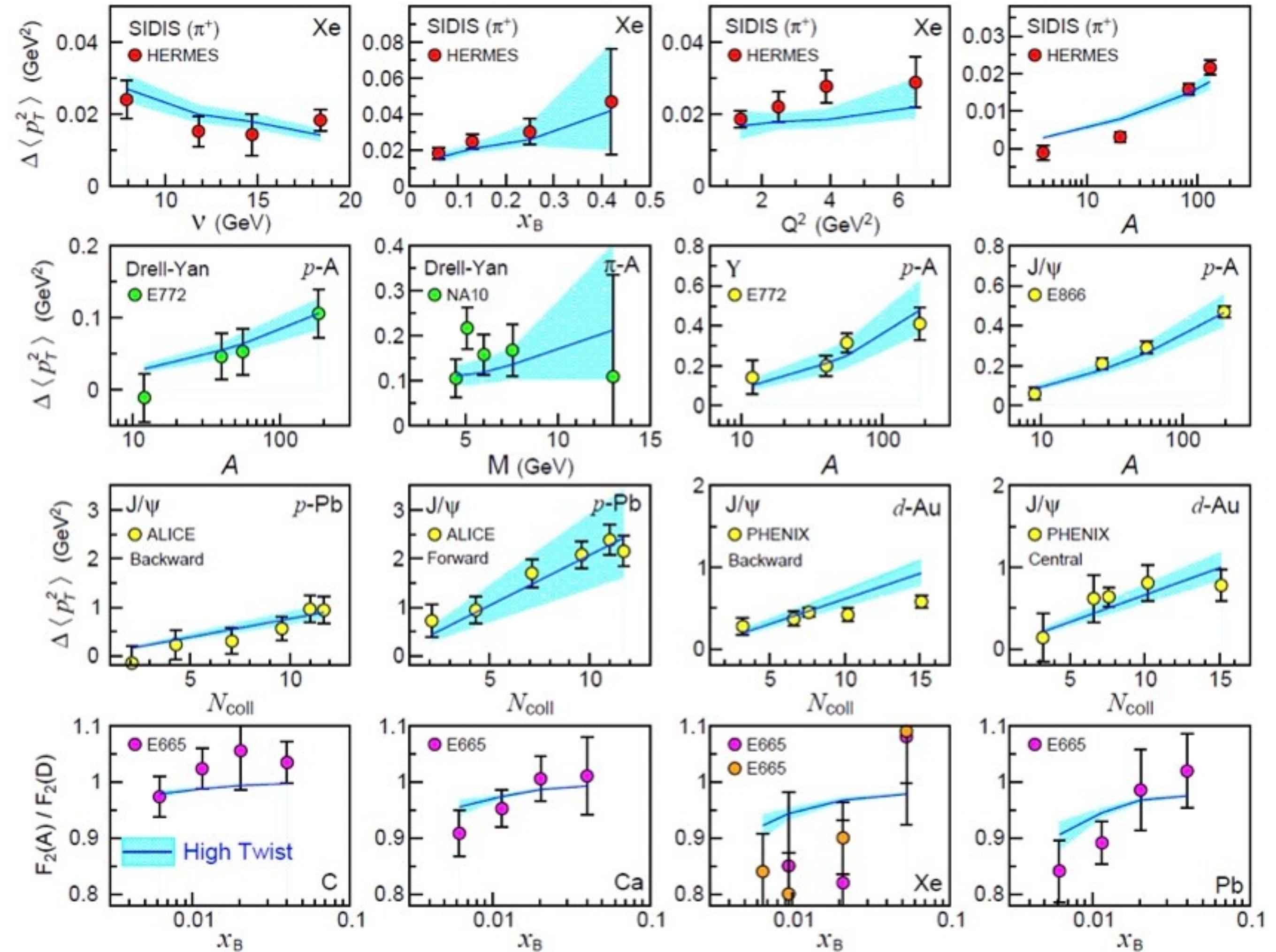
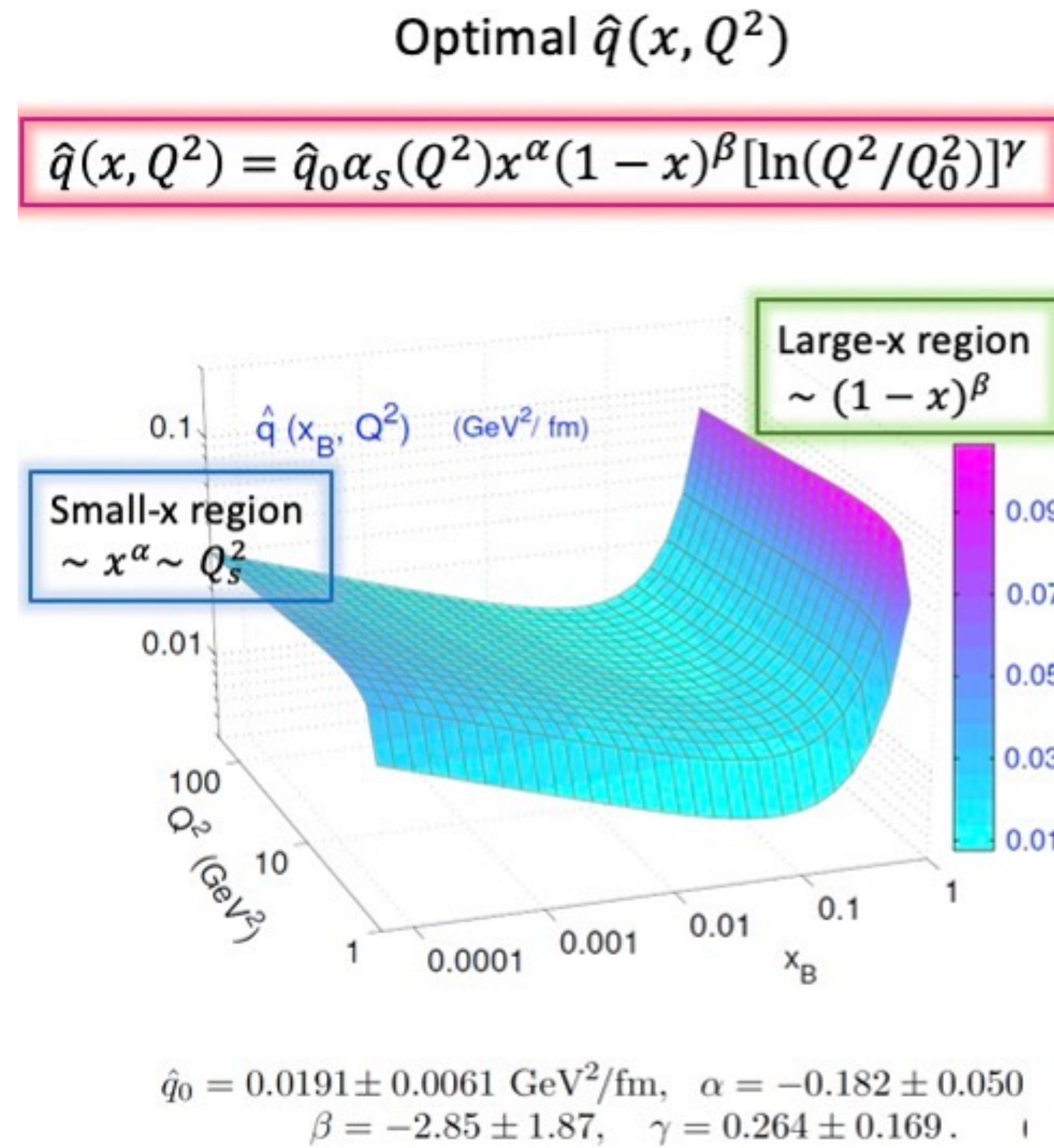
DY in pA



Heavy quarkonium in pA

Global analysis of jet transport parameter in CNM

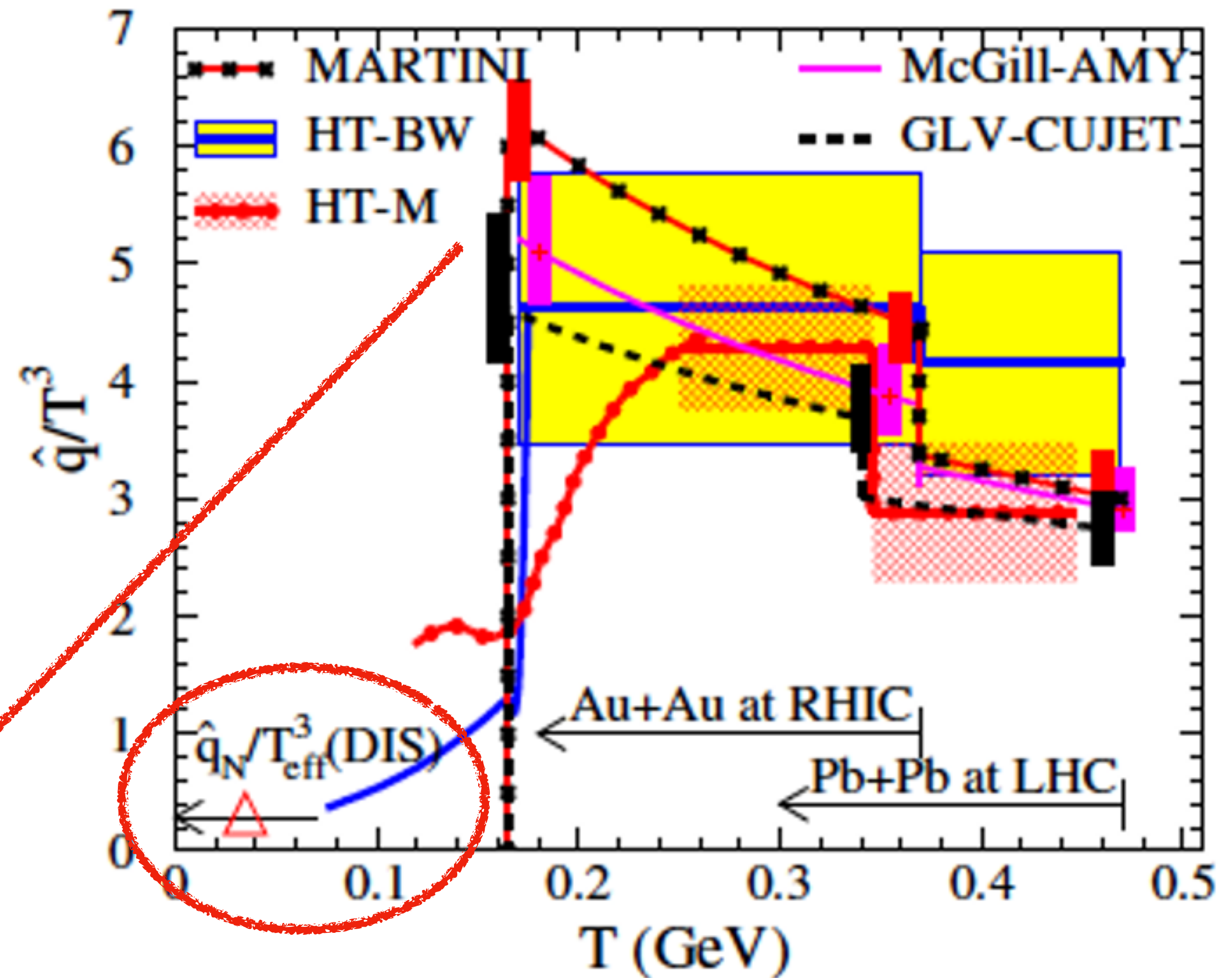
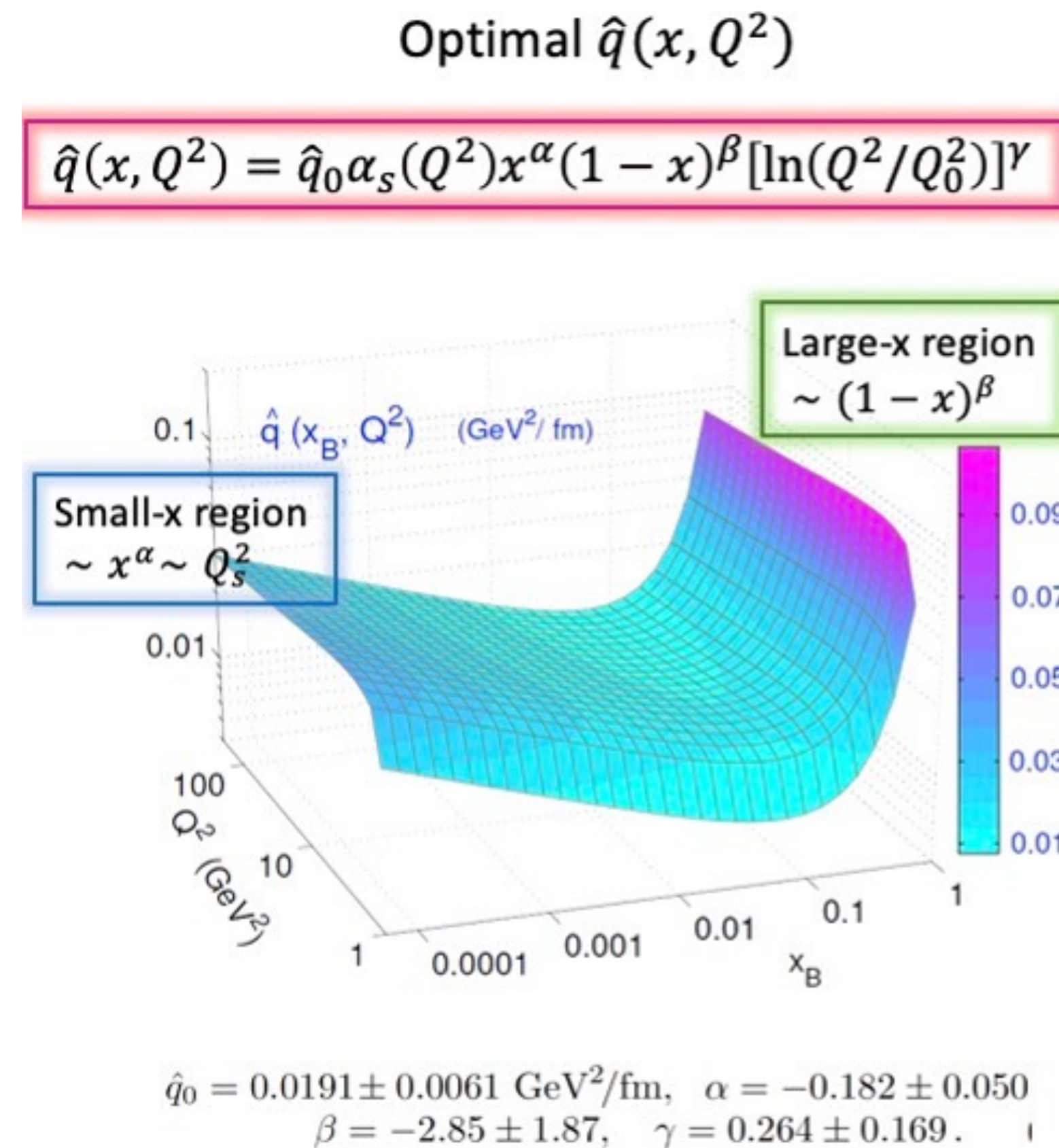
Ru, Kang, Wang, **HX** and Zhang, PRD 2021; 2302.02329



Gluon density in CNM is not a constant and order of magnitude smaller than QGP!

Global analysis of jet transport parameter in CNM

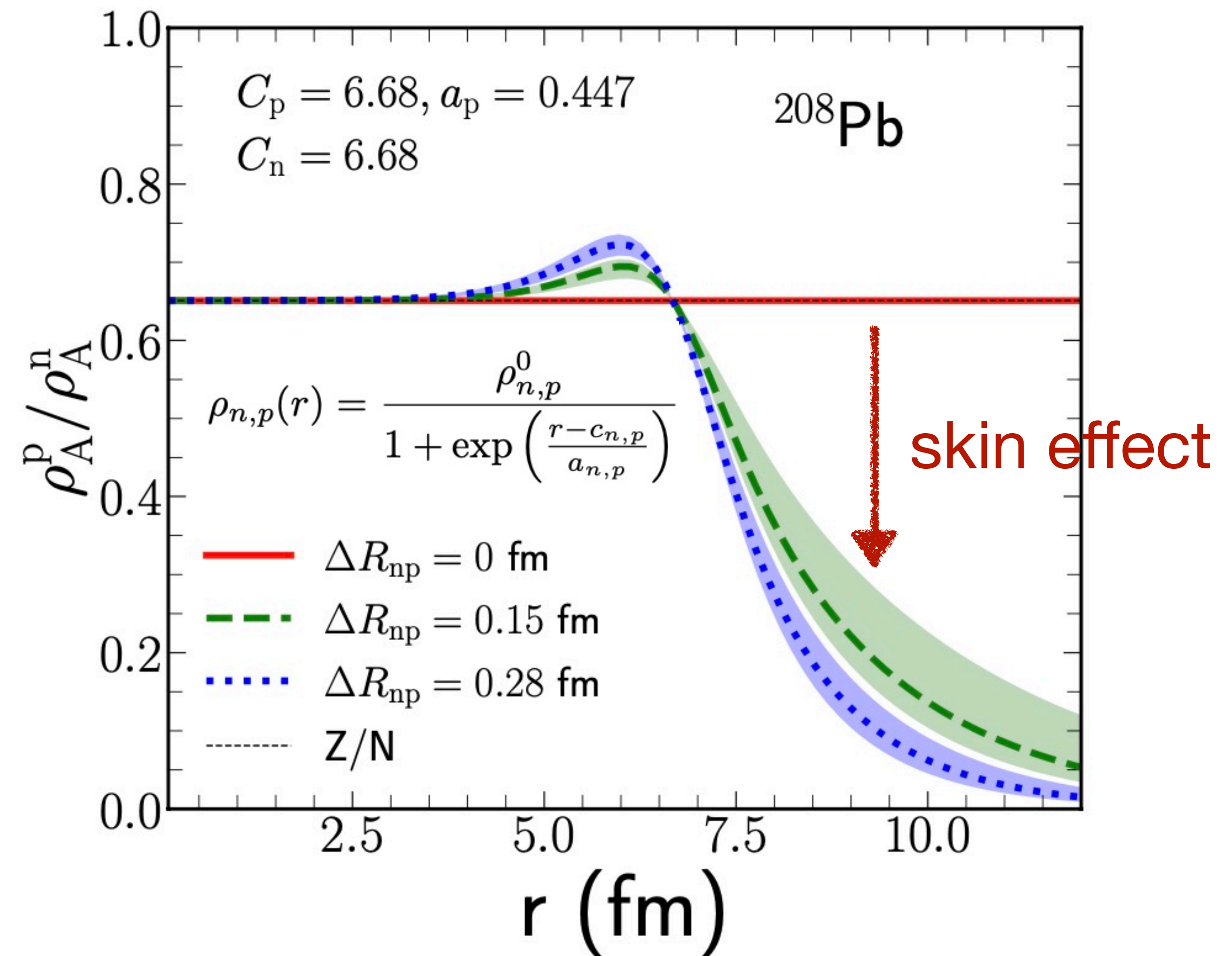
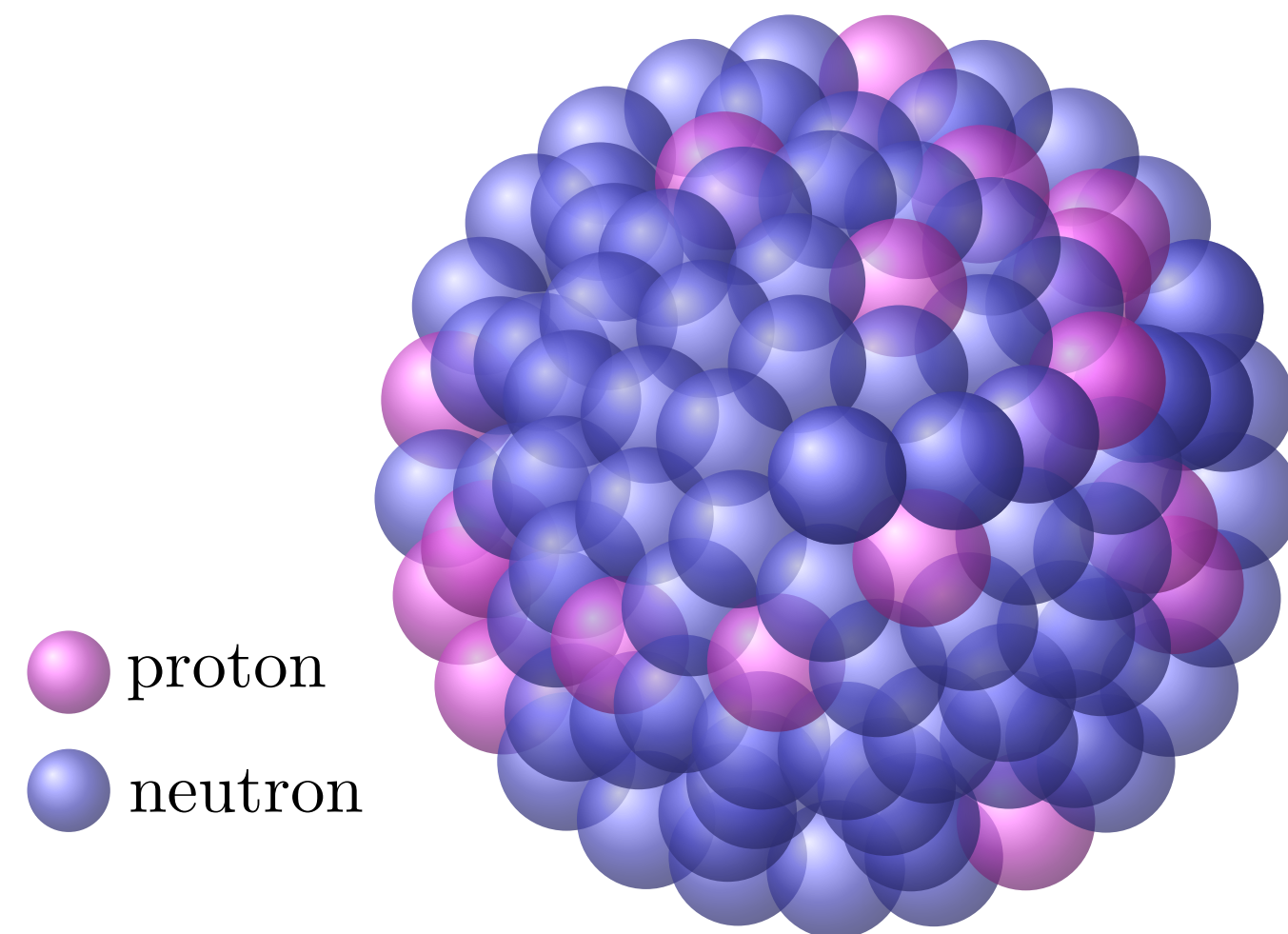
Ru, Kang, Wang, **HX** and Zhang, PRD 2021; 2302.02329



Jet transport at CEP? Talk by M. Huang

Neutron skin

◆ Woods-Saxon nuclear distribution



Neutron skin from **elastic scattering**

◆ Current knowledge on neutron skin

$$\Delta R_{np} = R_n - R_p$$

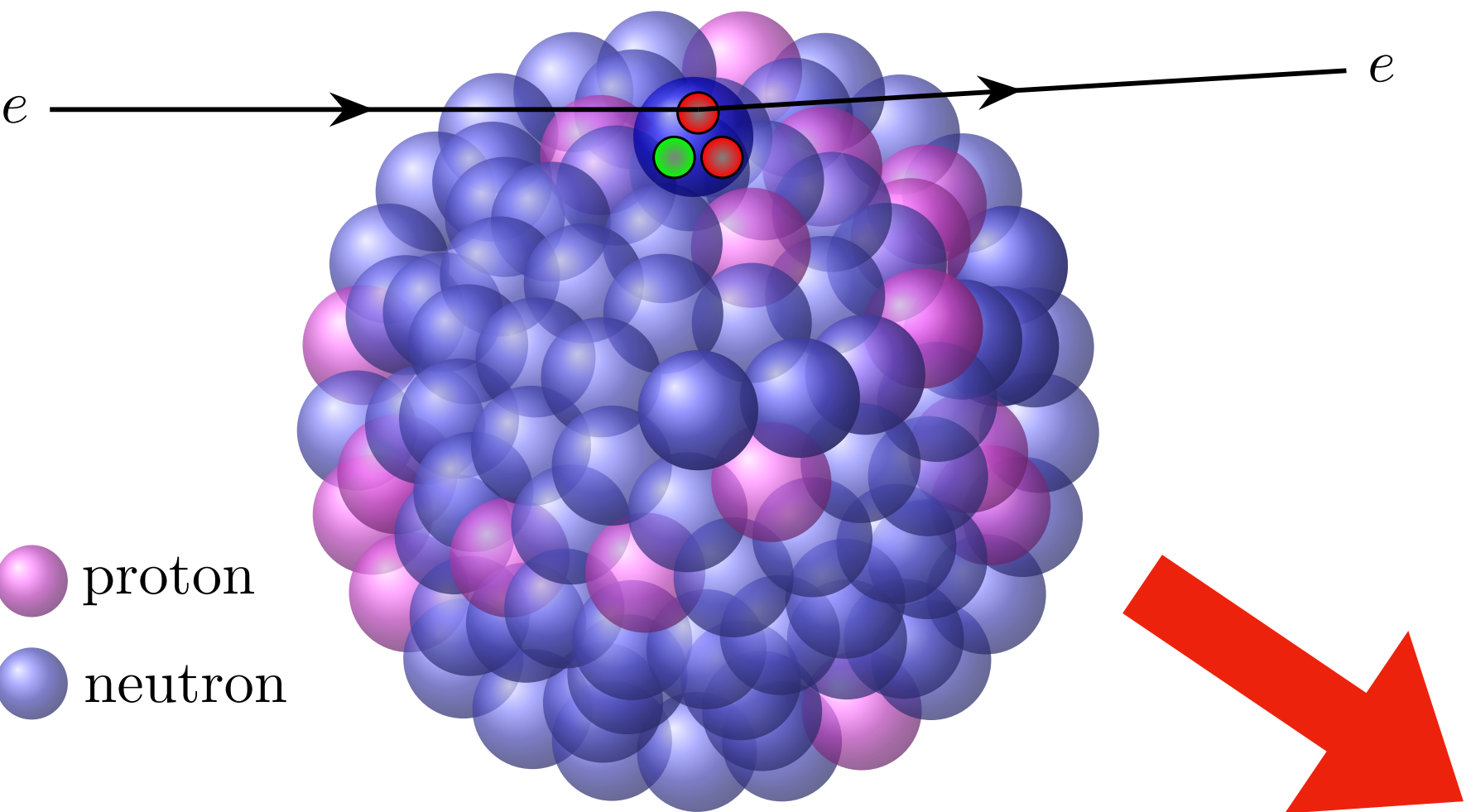


TABLE I. Values of the neutron skins in ^{208}Pb from a variety of experimental methods.

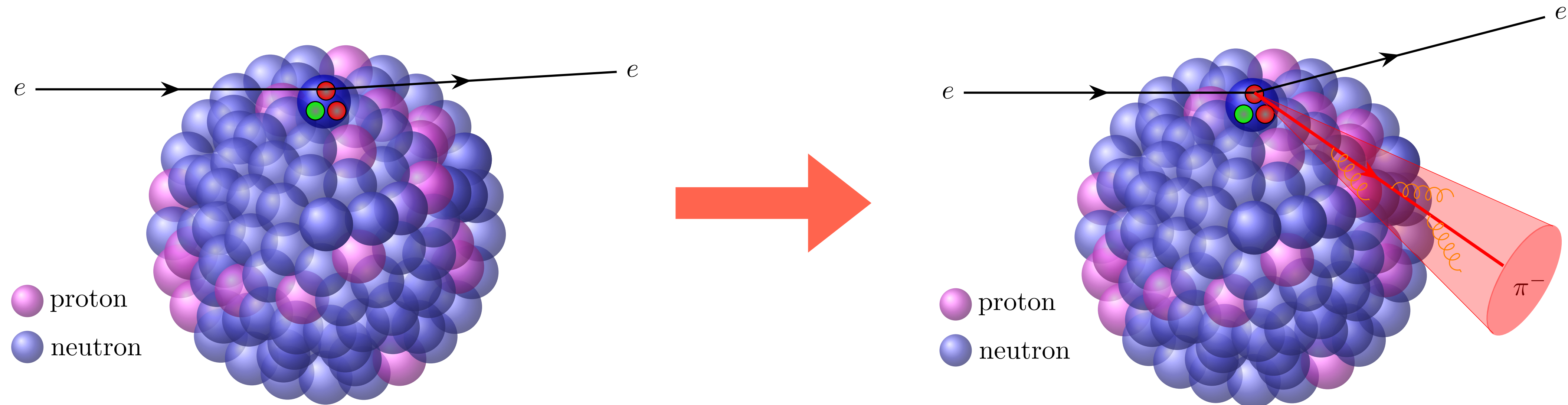
Type of measurement	Extracted neutron skin in ^{208}Pb
Proton-nucleus scattering [6]	0.083 - 0.111
Proton-nucleus scattering [7]	0.20 ± 0.04
Polarized proton-nucleus scattering [8]	0.16 ± 0.05
Polarized proton-nucleus scattering [9]	$0.211^{+0.054}_{-0.063}$
Pionic probes [10]	0.11 ± 0.06
Coherent π photoproduction [11]	$0.15 \pm 0.03^{+0.01}_{-0.03}$
Coherent π photoproduction [12]	$0.20^{+0.01}_{-0.03}$
Antiprotonic atoms [13]	$0.20 (\pm 0.04) (\pm 0.05)$
Antiprotonic atoms [14]	$0.16 (\pm 0.02) (\pm 0.04)$
Antiprotonic atoms [15]	0.15 ± 0.02
Electric dipole polarizability [16]	$0.13 - 0.19$
Electric dipole polarizability [17]	$0.165 (\pm 0.09)(\pm 0.013) (\pm 0.021)$
Electric dipole polarizability via polarized scattering at forward angle [18]	$0.156^{+0.025}_{-0.021}$
Pygmy dipole resonances [22]	0.18 ± 0.035
(α, α') GDR 120 MeV [23]	$0.19^{+0.09}$
parity-violating electron scattering [19]	$0.33^{+0.16}_{-0.18}$
parity-violating electron scattering [20]	0.283 ± 0.071

crucial for constraining the fundamental properties of cold nuclear matter and the equation of state of neutron star

Neutron skin from **deep inelastic scattering**

- ◆ A new proposal in deep inelastic scattering at EIC

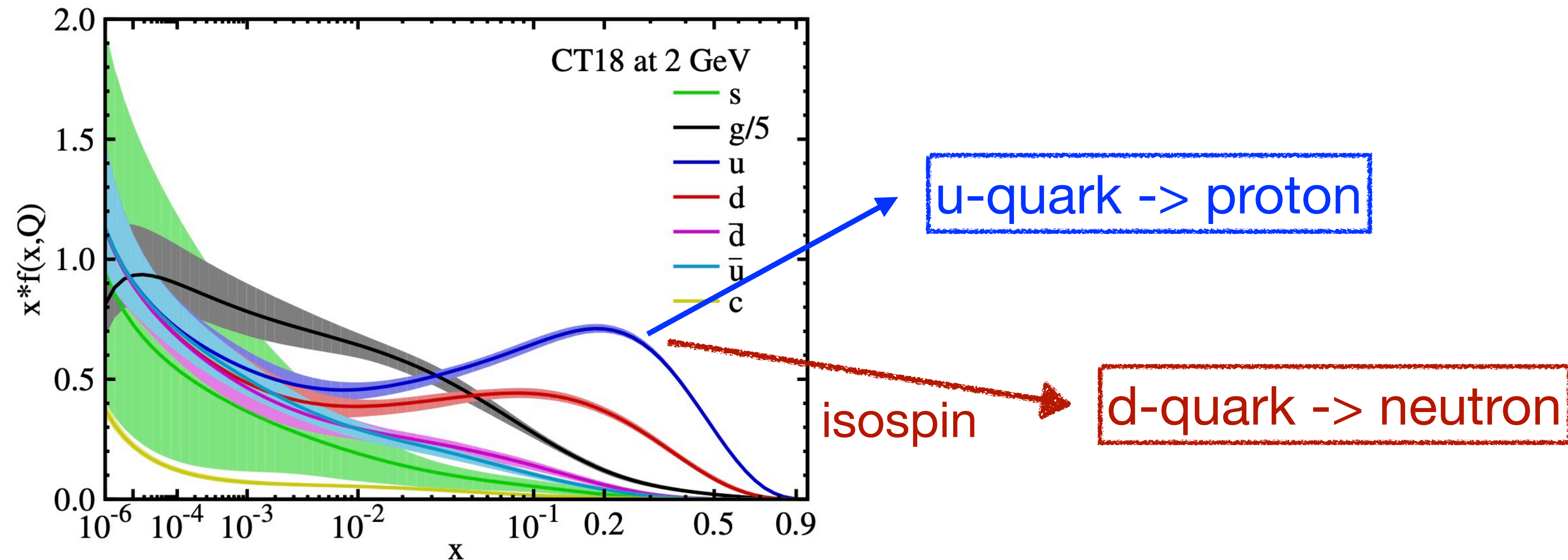
Zhang, Wang, Wang, **HX**, 2506.10694



Linking physics phenomena at both low and high collision energies

Neutron skin from **deep inelastic scattering**

- ◆ Using PDFs to tag flavor information of nucleon



- Correlation between struck nucleon and PDFs using isospin symmetry

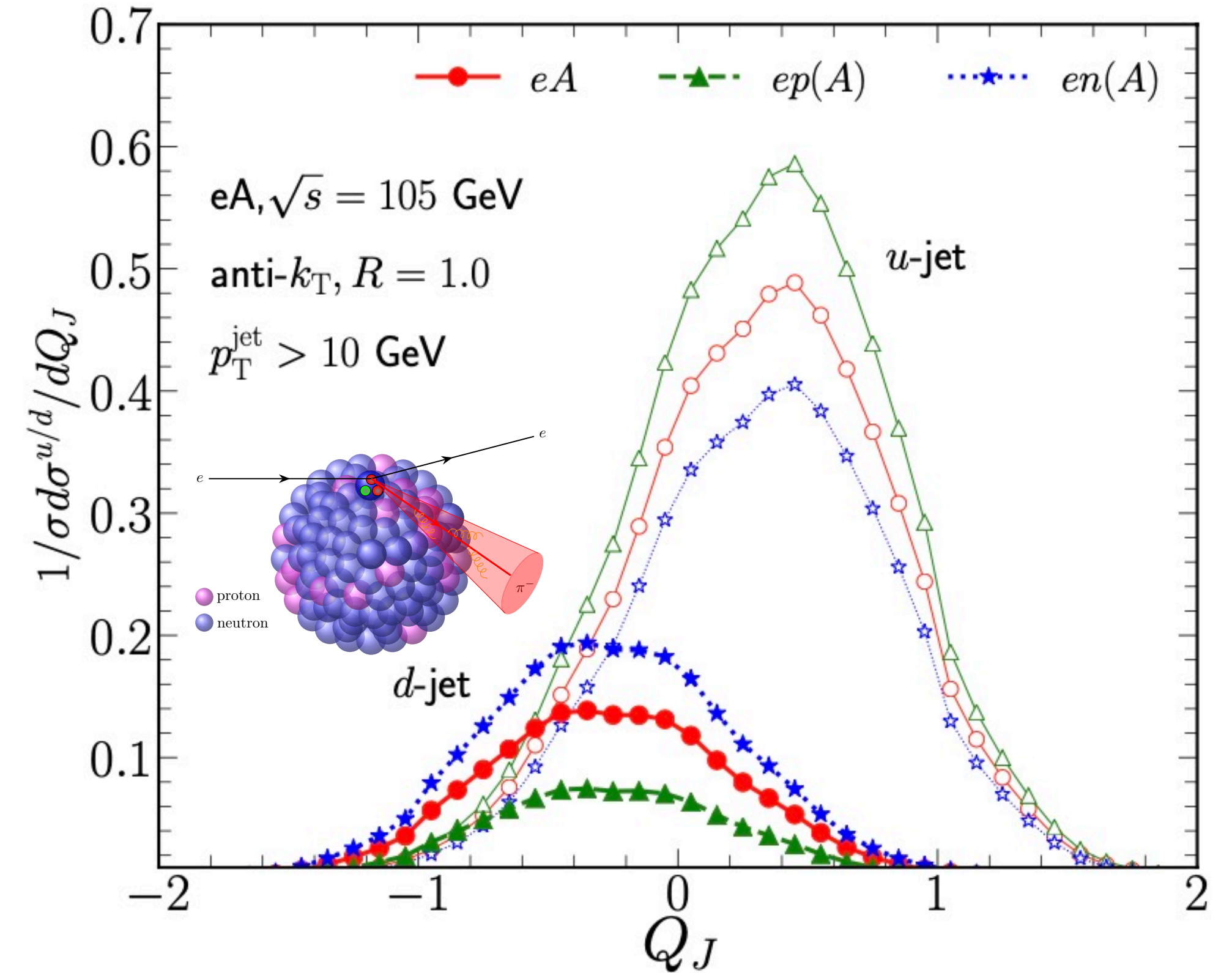
Neutron skin from **deep inelastic scattering**

◆ Jet charge in deep inelastic scattering

- TMD factorization

$$\frac{d\sigma}{dQ_J} = \sum_i e_i^2 \mathcal{F} \cdot \mathcal{T} \cdot \left\{ \tilde{f}_{i/A}(x, b_T) S_J(b_T, R) \right. \\ \left. \times H_{ei \rightarrow ei}(Q) \mathcal{G}_i(Q_J, p_T^J R) \right\},$$

$$Q_J = \sum_{h \in \text{jet}} \left(\frac{p_T^h}{p_T^J} \right)^\kappa Q_h$$

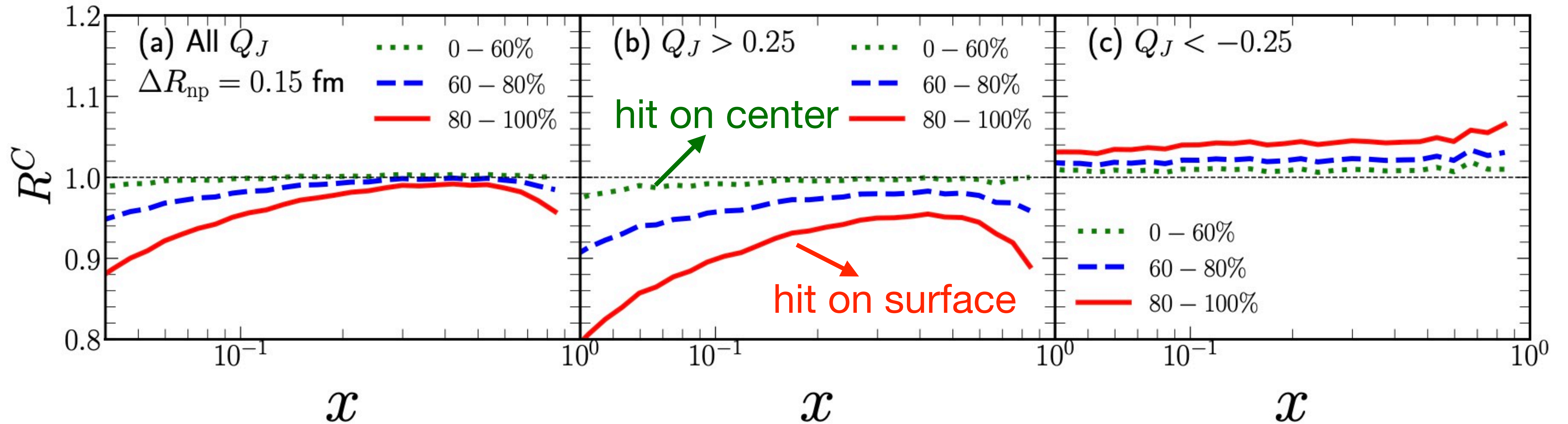


Intrinsic correlation between final-state jet charge distribution and initial-state partonic distributions in nucleons

Neutron skin from **deep inelastic scattering**

◆ Centrality-dependent nuclear modification

$$R^C(x, Q_J) = \frac{d\sigma^C / dx dQ_J}{d\sigma^{\text{MB}} / dx dQ_J}$$



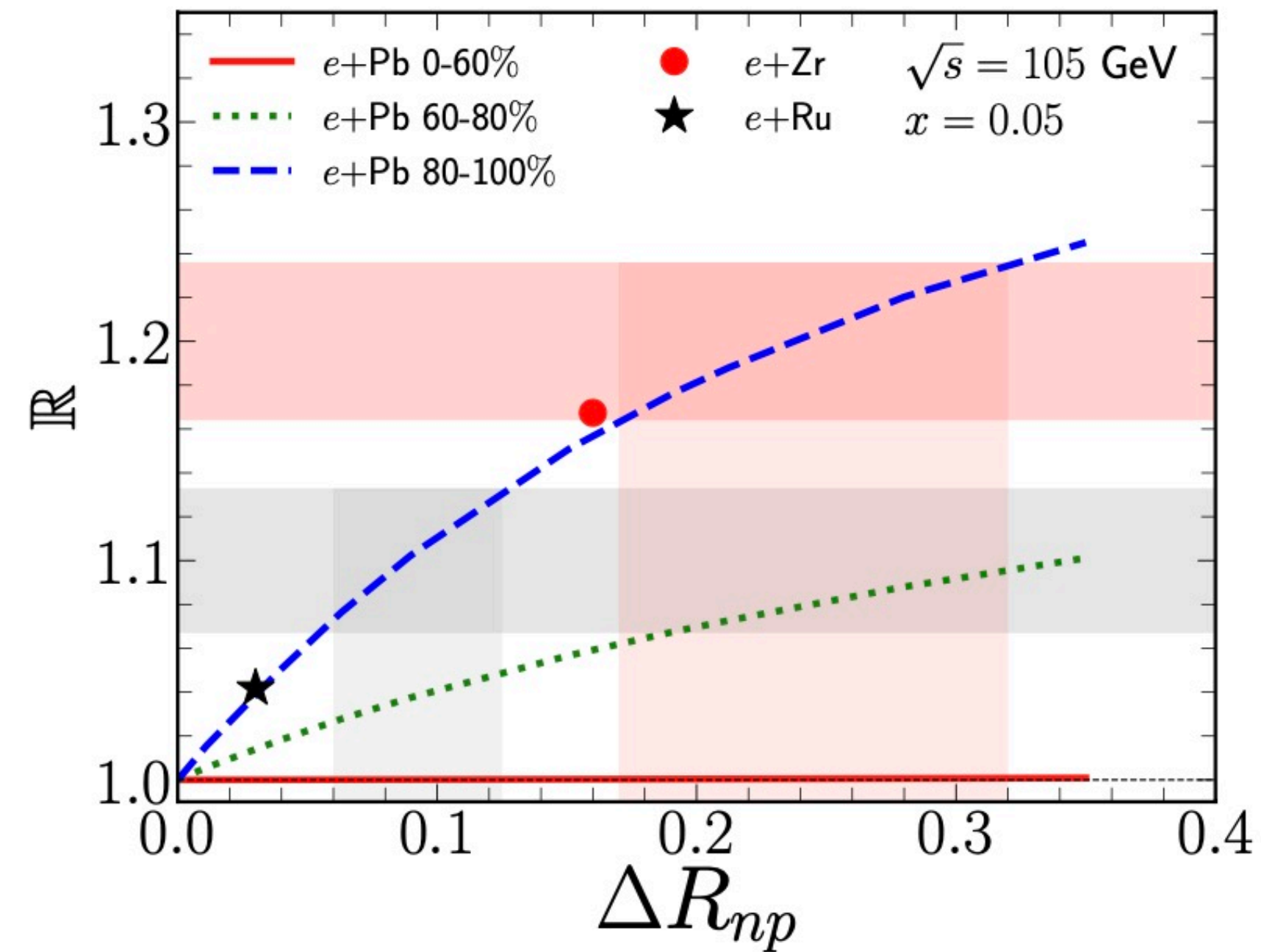
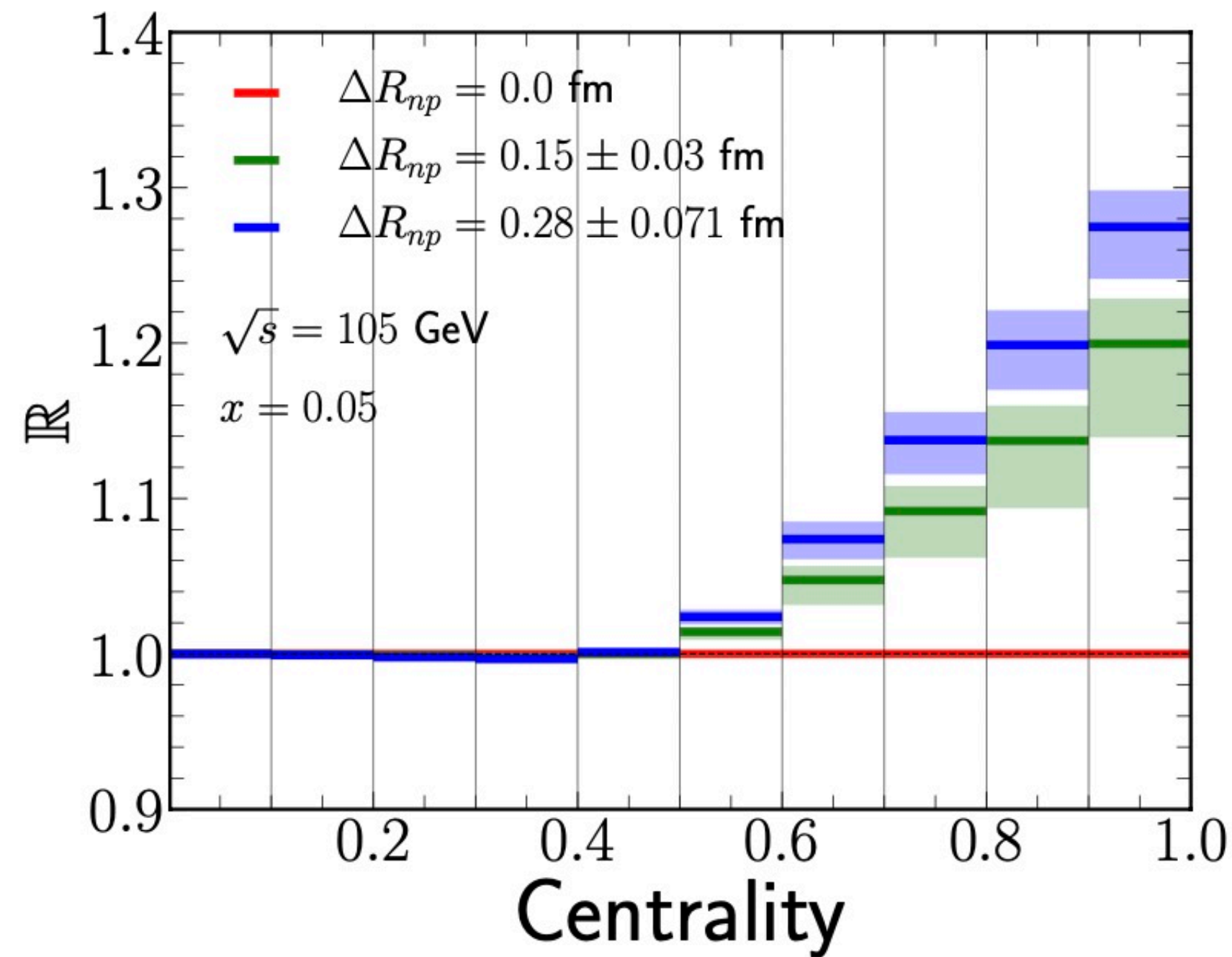
- Positive (negative) jet charge suppression (enhancement) in e+Pb collision
- A proxy for the spatial position of the struck nucleon within the nucleus

Neutron skin from **deep inelastic scattering**

◆ Centrality-dependent nuclear modification: double ratio

$$\mathbb{R} \equiv \frac{R^C(x, Q_J \leq -Q_c)}{R^C(x, Q_J \geq Q_c)} = \frac{d\sigma^C/dxdQ_J|_{Q_J \leq -Q_c}}{d\sigma^C/dxdQ_J|_{Q_J \geq Q_c}} \frac{d\sigma^{\text{MB}}/dxdQ_J|_{Q_J \geq Q_c}}{d\sigma^{\text{MB}}/dxdQ_J|_{Q_J \leq -Q_c}}$$

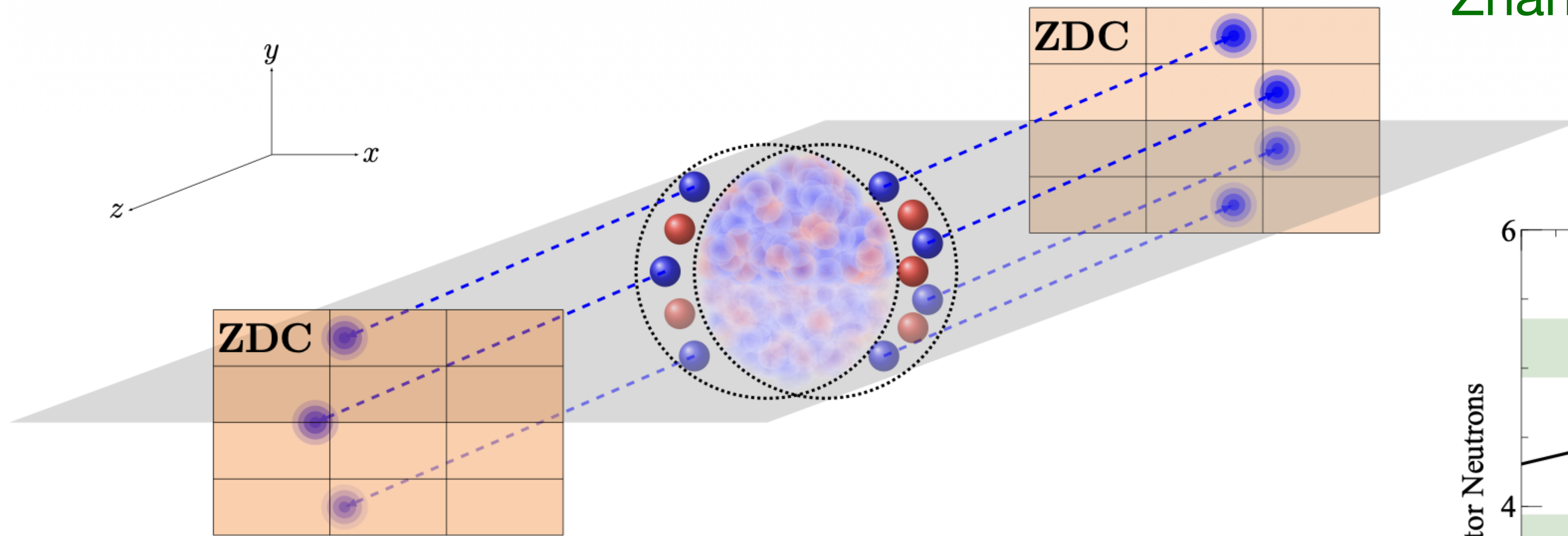
Zhang, Wang, Wang, **HX**, 2506.10694



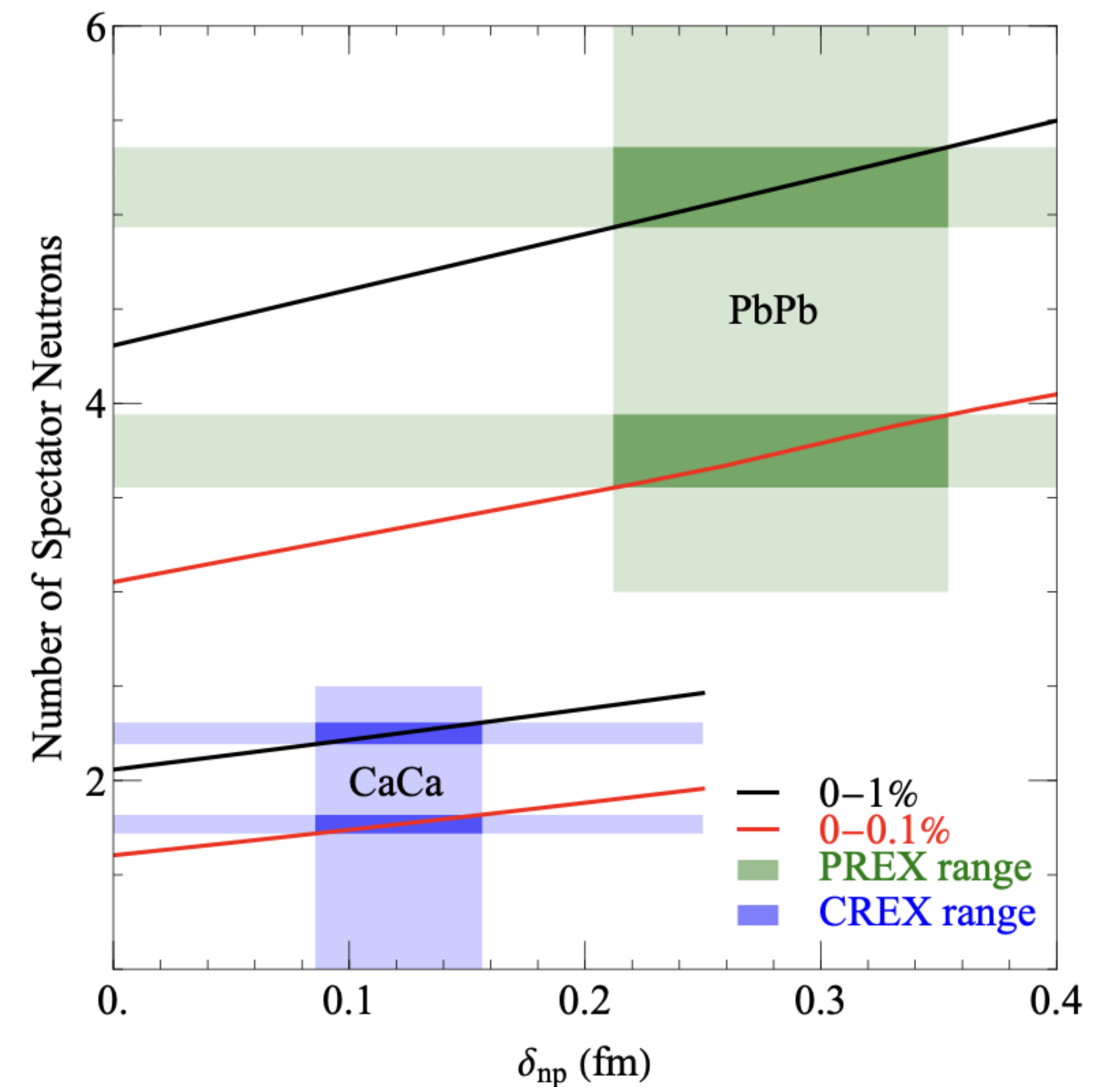
- Jet charge distribution in eA DIS: a novel probe for high precision determination of neutron skin thickness

Neutron skin effect in HIC

Zhang (张辉) et al., 2510.07816

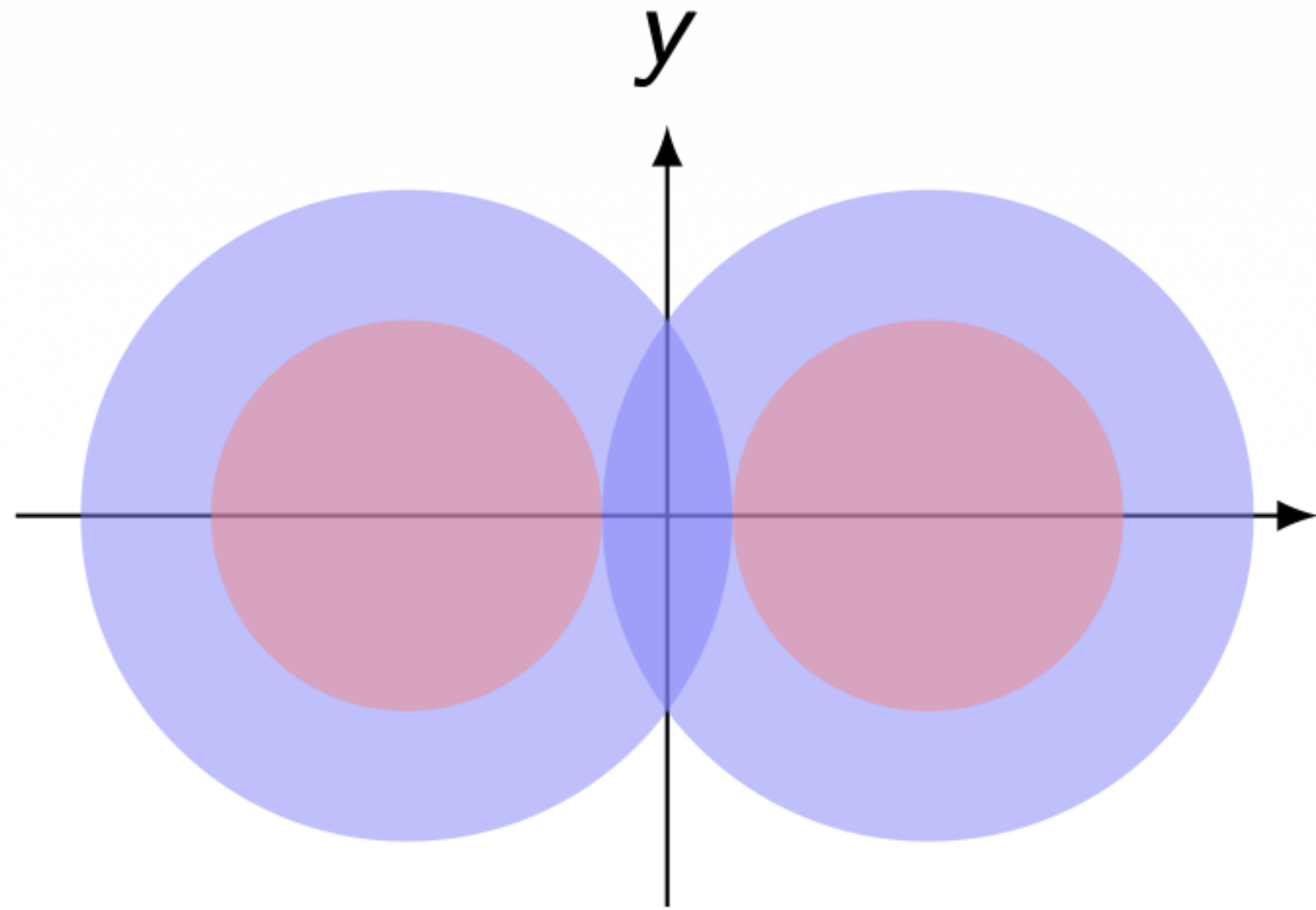


neutron skin effect for spectator
neutrons in super-central collisions

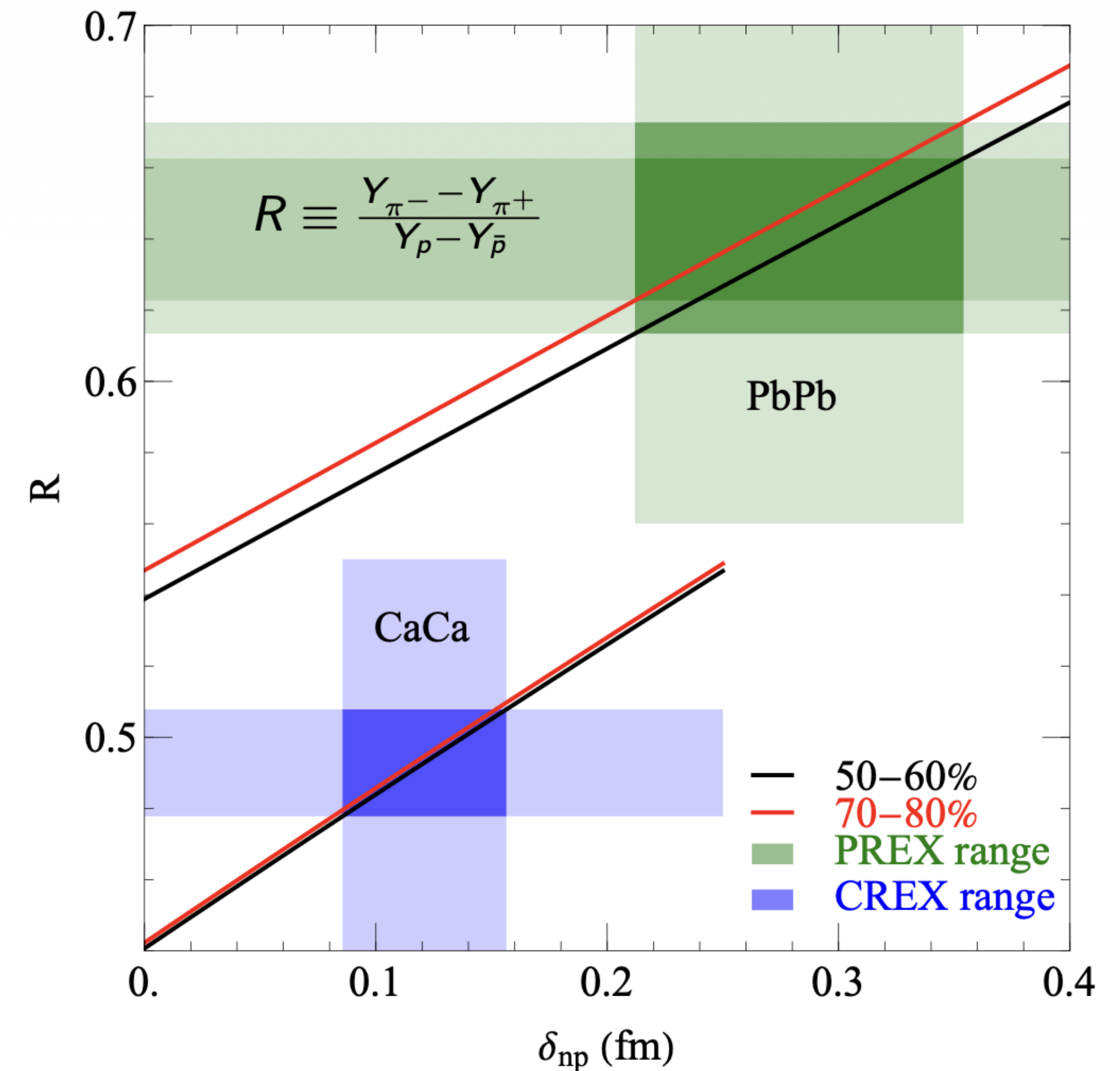


Neutron skin effect in HIC

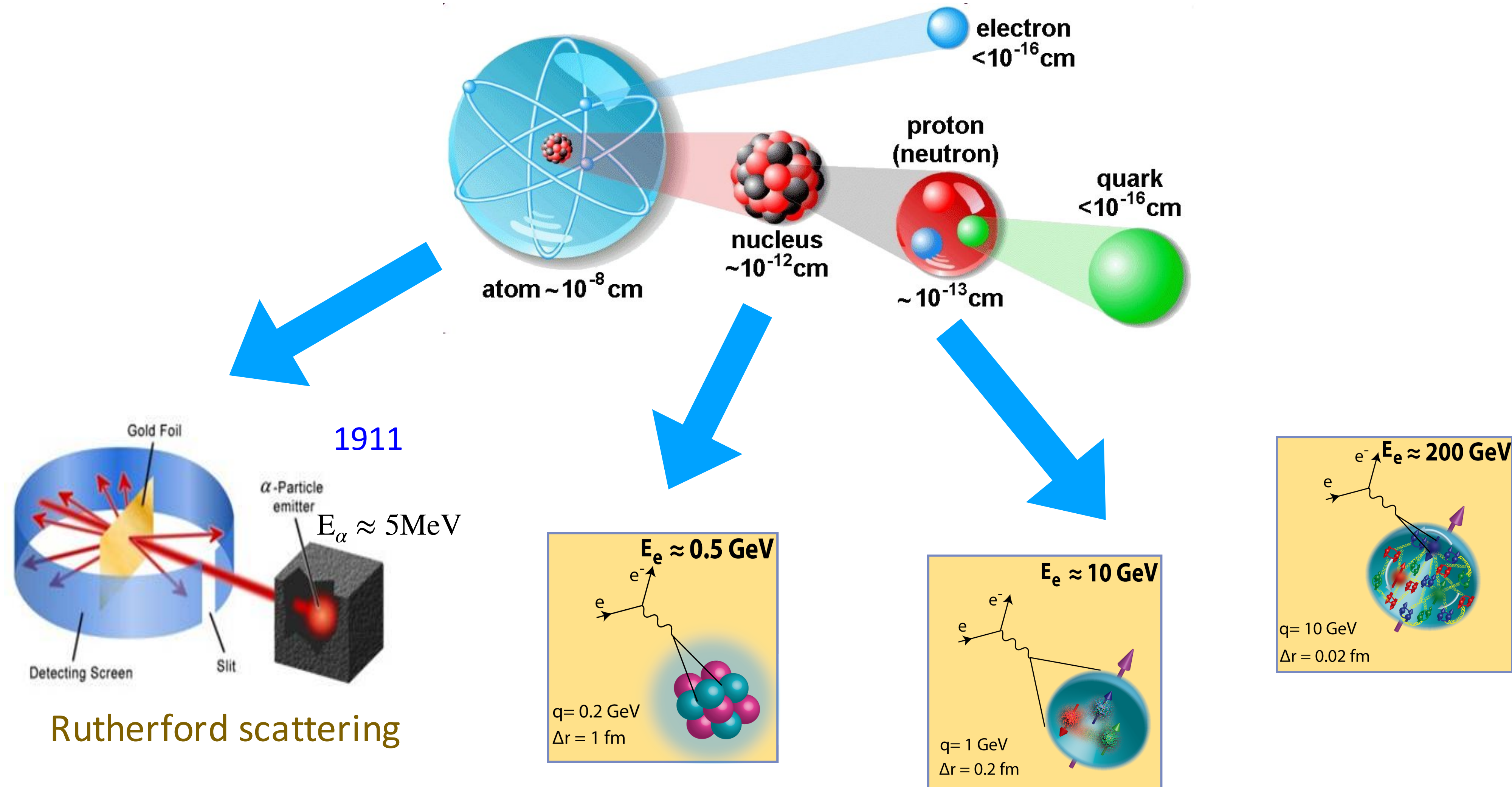
Zhang (张辉) et al., 2510.07816



neutron skin effect for pion asymmetry
in peripheral collisions



Summary



Probing nuclear structure at different scales in high energy scatterings



Thanks for your attention!

Backup

◆ Nuclear PDFs

$$f_{i/A}(x, \mu; b) = \frac{T_A^p(b)}{T_A(b)} f_i^{p/A}(x, \mu) + \frac{T_A^n(b)}{T_A(b)} f_i^{n/A}(x, \mu)$$

Thickness function: $T_A(b) = \int dz \rho_A(r)$

◆ Woods-Saxon parameters

TABLE I. WS parameters and neutron skin thickness for $^{208}_{82}\text{Pb}$, $^{96}_{44}\text{Ru}$ and $^{96}_{40}\text{Zr}$ used in our numerical calculations.

nucleus	c_p [fm]	a_p [fm]	c_n [fm]	a_n [fm]	ΔR_{np}
$^{208}_{82}\text{Pb}$ [7]	6.68	0.448	6.69	0.448	0
$^{208}_{82}\text{Pb}$ [7]	6.68	0.448	6.69	$0.566^{+0.028}_{-0.045}$	0.15 ± 0.03
$^{208}_{82}\text{Pb}$ [10]	6.68	0.448	6.69	$0.654^{+0.044}_{-0.046}$	0.28 ± 0.071
$^{96}_{44}\text{Ru}$ [21]	5.06	0.493	5.075	0.505	0.03
$^{96}_{40}\text{Zr}$ [21]	4.915	0.521	5.015	0.574	0.16

$$\rho_{n,p}(r) = \frac{\rho_{n,p}^0}{1 + \exp\left(\frac{r - c_{n,p}}{a_{n,p}}\right)}$$

Nuclear partonic structure - 3D imaging

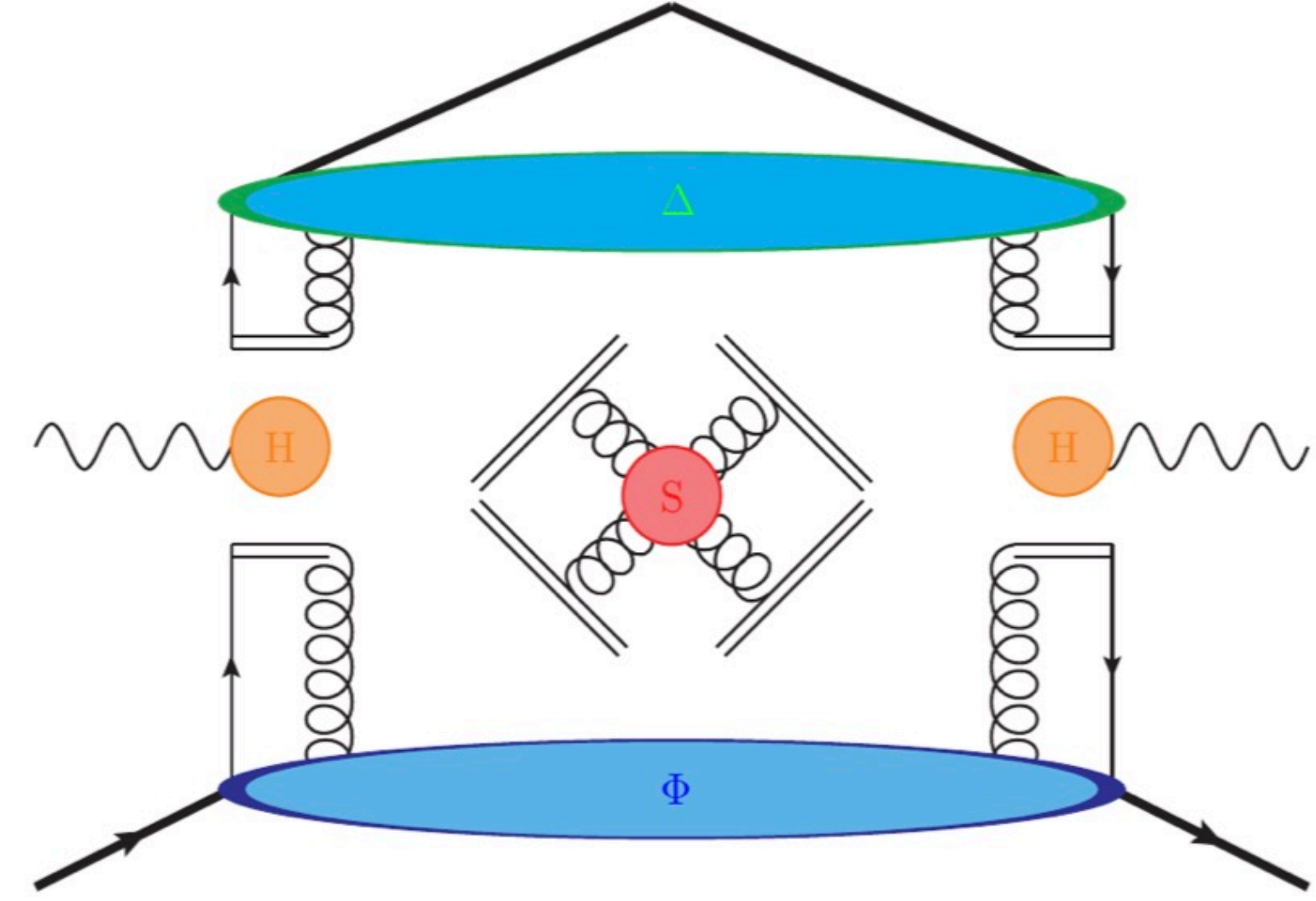
◆ TMD factorization for cross section

$$\frac{d\sigma^A}{dx dQ^2 dz d^2P_{h\perp}} = \sigma_0 H(Q) \sum_q e_q^2 \int_0^\infty \frac{b db}{2\pi} J_0\left(\frac{bP_{h\perp}}{z}\right) f_{q/n}^A(x, b; Q) D_{h/q}^A(z, b; Q)$$

◆ TMDs

$$f_{q/n}^A(x, b; Q) = \left[C_{q\leftarrow i} \otimes f_{i/n}^A \right] (x, \mu_{b_*}) \exp \left\{ -S_{\text{pert}}(\mu_{b_*}, Q) - S_{\text{NP}}^f(b, Q, A) \right\}$$

$$D_{h/q}^A(z, b; Q) = \frac{1}{z^2} \left[\hat{C}_{i\leftarrow q} \otimes D_{h/i}^A \right] (z, \mu_{b_*}) \exp \left\{ -S_{\text{pert}}(\mu_{b_*}, Q) - S_{\text{NP}}^D(b, z, Q, A) \right\}$$



Our assumptions

- Perturbative information is left unchanged by the nuclear medium.
 $C_{q\leftarrow i}$, $\hat{C}_{i\leftarrow q}$, and S_{pert} are unchanged.
- Non-perturbative information is modified.
 $f_{i/n}^A$, $D_{h/i}^A$, S_{NP}^D , and S_{NP}^f are altered.

Nuclear partonic structure - 3D

◆ **TMDs**

$$f_{q/n}^A(x, b; Q) = \left[C_{q \leftarrow i} \otimes f_{i/n}^A \right] (x, \mu_{b_*}) \exp \left\{ -S_{\text{pert}}(\mu_{b_*}, Q) - S_{\text{NP}}^f(b, Q, A) \right\}$$
$$D_{h/q}^A(z, b; Q) = \frac{1}{z^2} \left[\hat{C}_{i \leftarrow q} \otimes D_{h/i}^A \right] (z, \mu_{b_*}) \exp \left\{ -S_{\text{pert}}(\mu_{b_*}, Q) - S_{\text{NP}}^D(b, z, Q, A) \right\}$$

Collinear Distributions

We use the EPPS16 parameterization for $f_{i/n}^A$ (NLO). EPPS, EPJC 2017

We use the LIKE_n parameterization for $D_{h/i}^A$ (NLO). Zurita, 2021

Perturbative order in our analysis

Work at NLO+NNLL for the TMDs.

Non-perturbative parametrization

$$S_{\text{NP}}^f(b, Q, A) = S_{\text{NP}}^f(b, Q) + a_N \left(A^{1/3} - 1 \right) b^2$$
$$S_{\text{NP}}^D(z, b, Q, A) = S_{\text{NP}}^D(z, b, Q) + b_N \left(A^{1/3} - 1 \right) \frac{b^2}{z^2}$$

Generalized factorization formalism

$$\begin{array}{l}
 \text{perturbative expansion} \rightarrow \\
 \sigma_{phys}^h = \left[\alpha_s^0 C_2^{(0)} + \alpha_s^1 C_2^{(1)} + \alpha_s^2 C_2^{(2)} + \dots \right] \otimes T_2(x) \\
 \text{power expansion} \downarrow + \frac{1}{Q} \left[\alpha_s^0 C_3^{(0)} + \alpha_s^1 C_3^{(1)} + \alpha_s^2 C_3^{(2)} + \dots \right] \otimes T_3(x) \\
 + \frac{1}{Q^2} \left[\alpha_s^0 C_4^{(0)} + \alpha_s^1 C_4^{(1)} + \alpha_s^2 C_4^{(2)} + \dots \right] \otimes T_4(x) \\
 + \dots
 \end{array}$$

- Nuclear enhanced power correction
J. Qiu, G. Sterman, NPB 1990
J. Qiu, X. Luo, PRD 1998
Kang, Wang, Wang, **HX**, PRL 2014

$$\frac{1}{Q^2} \rightarrow \frac{A^{1/3}}{Q^2}$$

- Only one hard scale: Q^2
- High twist collinear factorization - nuclear modification from multiple scattering
- SIDIS: A direct probe of the nuclear quark-gluon quantum correlation

$$\Delta \langle \ell_{hT}^2 \rangle = \langle \ell_{hT}^2 \rangle_{eA} - \langle \ell_{hT}^2 \rangle_{ep} = \left(\frac{4\pi^2 \alpha_s}{N_c} z_h^2 \right) \frac{\sum_q e_q^2 T_{qg}(x_B, 0, 0) D_{h/q}(z_h)}{\sum_q e_q^2 f_{q/A}(x_B) D_{h/q}(z_h)}$$

- Twist-4 matrix element:
$$\begin{aligned}
 T_{qg}(x_1, x_2, x_3) &= \int \frac{dy^-}{2\pi} e^{ix_1 p^+ y^-} \int \frac{dy_1^- dy_2^-}{4\pi} e^{ix_2 p^+ (y_1^- - y_2^-)} e^{ix_3 p^+ y_2^-} \theta(y_2^-) \theta(y_1^- - y^-) \\
 &\times \langle A | \bar{\psi}_q(0) \gamma^+ F_\sigma^+(y_2^-) F^{\sigma+}(y_1^-) \psi_q(y^-) | A \rangle.
 \end{aligned}$$